Experimental assessment and evaluation of capacity degradation in energy sources for electrified propulsion systems

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Abstract. Lithium-ion (Li-ion) batteries are widely considered an efficient energy source for different propulsion systems for ground, aerial, and space vehicles due to their high specific energy and power. Capacity fading of Li-ion batteries represents a significant increase in running costs of electrified powertrains and hence grasps the attention of many researchers to investigate and understand this process closely. This paper presents an experimental method for monitoring, evaluating, and assessment of the capacity degradation process in vehicular energy storage systems. To this aim, a test rig has been designed and set up to conduct a set of predefined charging and discharging cycles according to respective standards to capture the changes in current throughput and voltage per cycle. The analysis reveals valuable insights into the correlation between the rate of battery discharge current and the rate of capacity loss of Li-ion batteries. Moreover, such results are beneficial to develop accurate degradation models of the batteries using different machine learning techniques, to be used for mathematical modeling of electrified propulsion systems.

1. Introduction

Environmental sustainability has been a significant concern in alternative and advanced propulsion systems for different types of ground, naval, aerial, and space vehicles. Emissions from the combustion of fossil fuels are a significant source of urban pollution [1]. In 2008, civil aviation released around 2% of carbon dioxide emissions into the atmosphere [2]. Furthermore, conventional propulsion has low efficiency. Hence, traditional propulsion problems represent political, environmental, and economical. So the aircraft industry tends to create alternative power sources that affect the environment [3].

The main potential alternative for conventional propulsion systems is electrified powertrains. Electric power sources certainly fulfill the requirements of a clean environment, as generating electric energy is more convenient than relying on clean and renewable sources. A report in 2020 for The International Energy Agency outlined the electricity generating sources in the European Union: 1.4% oil, 14.9% coal, 20.2% gas, 20.5% nuclear, and 43% renewables. Despite the different figures for energy after the COVID-19 pandemic, electric power is still the best considering environmental and economic impacts [4].

The main challenge facing electric power systems is the efficiency and lifetime of energy storage systems. The onboard storage of electric energy for propulsion systems can typically be using ultra-capacitors and electric batteries. This study focuses on the battery, considering the battery is the primary and most commonly used storage system for electric propulsion systems. Batteries need continuous upgrading to cover the design requirement. The design needs lightweight, high energy density, less refilling time, and lower price. There is research on everything related to the battery, but this study will cover research on extending battery life. Because battery aging is a real problem, if battery aging reduces, the cost will be significantly mitigated.

Li-ion batteries became applicable for low earth orbit (LEO) missions in the early 2000s [5]. The requirement for batteries for adaptive (LEO) missions to have reliability exceeds five years and has to withstand harsh aerospace conditions. Aerospace has a cruel operating conditions such as extreme vibration during take-off, temperature, vacuum, radiation, and microgravity [6].The prediction end of life for the battery is necessary to avoid failure of the battery in space missions.

2. Degradation of Li-ion Batteries

Previous research in this regard covered various directions. Some researchers are concerned with the best power management to optimize the different energy systems to get the best performance of the hybrid systems in the power supply and thus extend battery life. Moreover, other research is devoted to researching the factors that affect battery life and work to reduce its severity by studying driving patterns and each factor separately to reduce battery degradation. The capacity degradation of Li-ion batteries will be reviewed in Some previous studies.

2.1. Degradation of energy sources

Different batteries have different internal chemical construction, which suits various applications. The main factors which control battery choosing are the cost, specific energy, specific power, thermal control, time of charging, and lifetime. Table 1 illustrates the advantages and disadvantages of selected aqueous batteries. The comprised characteristics in table 1 are cycle life, energy density, raw materials, toxicity, and columbic efficiency.

Table 1. Advantages and disadvantages of selected batteries.

Technology	Advantages	Disadvantages
Pb acid	Abundant raw materials-low cost	Limited cycle life-toxicity Low energy density
Ni-Cd	Moderate energy density Moderate coulombic efficiency	Memory effects Toxicity
Na-ion (λ-MnO_2/C)	High energy density- high round-trip efficiency-relatively long cycle life.	Little information Earlier development stage
Fe-air	Low cost- environmental friendliness- abundant raw materials- easy to scale up	Low coulombic efficiency Low energy density
NiFe	Long cycle life - abundant raw materials	low energy density Self-discharge
NiMH	Moderate energy density	Memory effects Low efficiency
Zn-air	High energy density- low cost- environmental friendliness- abundant raw materials	Short cycle life Low efficiency
Li-ion ($LiMn_2O_4$/VO_2)	High energy density- high round-trip efficiency- relatively long cycle life	High cost, safety issues Low Li abundance

The Li-ion batteries, Zn-air and Na-ion, have a high energy density, and Nife and Li-ion have long cycle life. Table 2 compares values of cost, energy, columbic efficiency, self-discharge, aging, and memory effect for merit aqueous batteries [3].The values illustrate that the Li-ion batteries have the highest coulombic efficiency, high cycle life, and low self-discharge, but the Comparison showed that the cost of the Li-ion battery is the highest. The Li-ion battery is a typical battery that has positive characteristics, so the Li-ion batteries are the best candidate for the Aerospace field. The Comparison in table 1 and table 2 illustrates that Competitive specifications qualify it to participate in many fields, such as using it in the aerospace field. It is precisely this area that this study is concerned with.

2.2. Influencing factors on the capacity degradation of batteries

Li-ion battery considers the most common use in most applications in recent decades. Li-ion battery not only used in the aerospace field but are also involved in computers, cell phones, power tools, and electric vehicles (EVs). Li-ion battery considers the higher-cost component in the application that works with them [7]. So the lifetime of the Li-ion battery is an essential factor in increasing the reliability of li-ion battery usage.

The battery's degradation leads to capacity reduction, self-discharge, and increasing internal resistance. For most products, 20 % capacity fading is considered the end of life (EOL) for batteries [8]. So, battery degradation has severe impacts on product performance. The battery's aging is affected by three main variables (temperature, state of charge (SOC), and current).

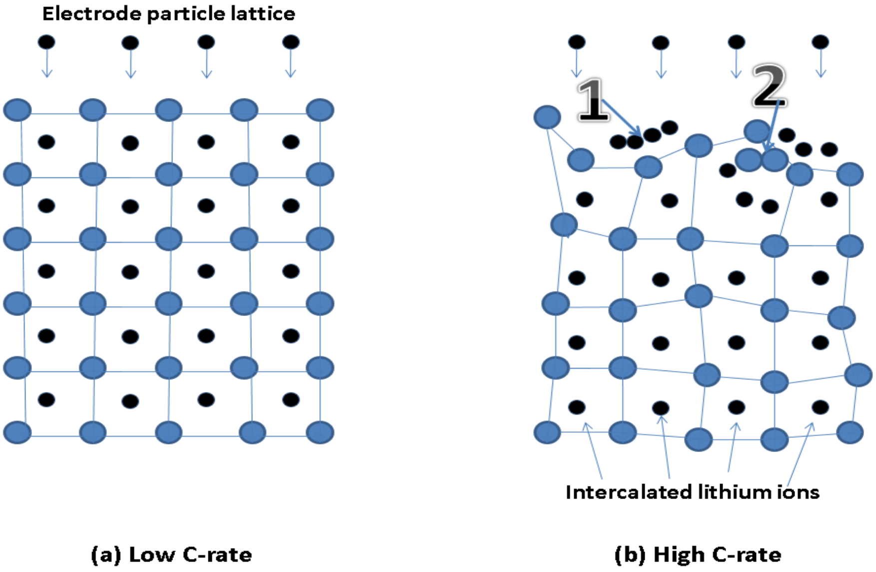

Figure 1. A comparison between (a) a low charging/discharging current and (b) a high discharging/charging current showing 1) lithium plating and 2) particle cracking[7].

The main challenge in this search is battery degradation. The temperature, SOC, and C-rate are the main factor in battery degradation. This study concerns the effect of the C-rate on battery life. The design requirements for c-rate are complicated. The variety of aircraft designs needs a wide range of C-rate, so it must identify the effect of C-rate on battery degradation through experimental study.

Identification for degradation behavior needs to multi and complicated tests. This paper is concerned with the effect of c-rate on battery health. For applying the c-rate test, it needs many cycles to identify the behavior of degradation. The test structure is about the charge and discharge processes with different loads. The test rig is designed to run the cycles automatically and store the data for each cycle on the memory module. The stored data is about current, volt, and temperature each second. The data is analyzed with a mathematical program to monitor capacity fade.

Table 2. A comparison for values of cost, energy, coulombic efficiency, self-discharge, aging, and memory effect for batteries.

Technology	Cost [€kwh^{-1}]	Energy density [$wh\ kg^{-1}$]	Efficiency [%]	Self-discharge[% $month^{-1}$]	Life [cycle]	Memory effect
Pb acid	25-40	30-50	50-70	30	300-500	No
Ni-Cd	70-80	50	65-70	28	1500	Yes
Na-ion (λ-MnO2/C)	300-400	50-60	60	-	-	-
Fe-air	5-10	60-80	45	20	300	No
NiFe	50-60	30-50	55-65	20	2000+	No
NiMH	275-550	50-80	65	30	500-800	Yes
Zn-air	5-10	350-500	50	20	200-600	No
Li-ion (LiMn2O4/VO2)	500-700	75	60	10	500-3000	Small

3. Standard tests for capacity measurement and evaluation

Many tests were conducted on the battery to extend its lifetime. Manufacturers do not know the perfect ranges of battery operation, so battery tests are necessary to identify battery degradation behavior. This section will focus on tests concerned with the effect of temperature, state of charge, and c-rate on the battery.

Table 3: The values of capacity loss at different temperature values during cycling (0-100%) and storage.

Cell characteristics							
Shape	**Technology**	**Capacity [Ah]**	**Test type**	**Temperature [°C]**	**Capacity loss[%]**	**Test period cycles/ days**	**Study**
Flat (Pouch)	NMC/graphite	40	cycling	23	20	2600 cycles	[9]
				45		2000 cycles	
				45/65(charge /discharge)		800 cycles	
Cylindrical (18650)	1:1 NMC+ LMO/graphite	1.5	Cycling	25	20	+65 days	[10]
				50		50 days	
				60		35 days	
				70		25 days	
				0		22 days	
				-10		10 days	
				-20		7 days	
Cylindrical (26650)	LFP/graphite	2.85	Storage test (stored at 100% SOC)	10,15	3.7	230 days	[11]
				25	4.6	230 days	
				35	5	150 days	
				45	5.9	100 days	
				55	7	70 days	
Cylindrical (18650)	NMC+ LMO/graphite	2.15	Storage test (stored at 50% SOC)	25	1	365 days	[12]
				45	7		
				60	30		

3.1. Temperature tests

Temperature is the main factor in Li-ion battery aging. Most studies illustrate that the Li-ion operation range is between 0°c as the minimum operating range and 60°c as the maximum operating range. The Li-ion operation under 0°c increases cell impedance, and above 60°c leads to rapid capacity loss. Paper [8] mentioned the internal resistance increase five times at 60°c greater than at 25°c. Another study [13] recommended that the perfect range fur the charging process is between 15°c and 50°c. The paper [14] applied a semi-empirical model to illustrate the different impacts of ambient temperature and solar radiation. Table 3 illustrate the temperature effect on battery life span.

3.2. State of charge tests

Overcharging and discharge impact battery health, and Overcharging is the main reason for thermal runaway because of the additional charges directed to the battery.

Thermal runaway is the most critical safety issue. On the other hand, over-discharging causes rapid degradation. The charging process always aims for short-time charging, higher capacity utilization, good energy efficiency, and extended battery lifetime. Moreover, the discharge process aims to achieve the same targets as the charging processes, except the time should be as long as possible. So the optimization of charge and discharge is a complicated process. Table 4 illustrates the results of the previous studies for effect of different SOC on battery degradation.

Table 4: The values of capacity loss at different SOC during cycling and storage.

Cell characteristics							
Shape	**Technology**	**Capacity [Ah]**	**Test type**	**SOC[%]**	**Capacity loss[%]**	**Test period cycles/ days**	**study**
Flat (Pouch)	LCO/ graphite	1.5	Cycling (at 25 °C)	0-100	18	800 cycles	[15]
				20-80	10	800 cycles	
				40-100	11	750 cycles	
				20-80	9	750 cycles	
				0-60	3	750 cycles	
Cylindrical (26650)	LFP/graphite	2.85	Storage test (stored at 45 °C)	0	1.5	235 days	[11]
				25	4.4		
				40	5.6		
				75	6.2		
				100	8		
Cylindrical (18650)	LFP/graphite	1	Storage test (stored at 25 °C)	30	1	300 days	[16]
				60	3		
				100	5		
			Storage test (stored at 40 °C)	30	6		
				60	8		
				100	12		
			Storage test (stored at 55 °C)	30	15		
				60	21		
				100	25		

Many factors control in charging and discharging processes. These factors are represented in available time for charging, energy density, and desired DOD, which adapts with the designed application. A study [17] shows that the higher SOC and high temperature decrease the battery's lifetime.

Faria et al. recommended that SOC around 40% is the perfect range for long-time battery storage. Furthermore, with partial discharge, full discharge increases the degradation[18].

3.3. C-rate tests

The accumulated charge transfers in and out of the battery (c-rate) are considered a vital factor in battery degradation besides the temperature and SOC. The C-rate is relative to the total capacity of the battery [19]. The high C-rate in charge and discharge accelerates battery degradation. A high rate of discharge means Li-ion transfers in a short time which leads to lithium dendrite formation. High rate discharge also causes increasing internal cell temperature, therefore depleting the active material in the cell, so the high rate of discharge accelerates the degradation of the battery [20].

An experimental study [21] shows that the degradation mechanism depends on C-rate. The study [21] shows that forming additional Li-ion plating when charged with 3C, and gas evolution and graphite exfoliation result in a charge which 4C. Figure 1 shows the shape of lithium ions in low charging current and high charging current [7] .Figure 1 shows the homogeneous distribution of ions in the lattice through the low current charge and inhomogeneous distribution in the lattice through the high current charge. The high C-rate causes lithium plating on the electrode and stress due to active material lack and cracking. Table 5 shows the results of the previous studies for the effect of C-rate on battery health.

Table 5:The values of capacity loss at different C-rate during cycling and storage.

Cell characteristics			Test type	C-rate	Capacity loss[%]	Test period [cycles]	Study
Shape	**Technology**	**Capacity[Ah]**					
Cylindrical (18650)	LMO + NMC/graphite	1.25	Cycling (CCCV)	1A	20	900	[22]
				3A	20	750	
				5A	20	550	
Cylindrical (18650)	NMC + LCO /graphite	1.1		1A	20	1050	
				3A	20	1000	
					20		
				5A	20	975	
Cylindrical (18650)	LFP/graphite	1.1		1A	2	1200	
				3A	4	1200	
				5A	30	750	
Cylindrical (18650)	LCO/graphite	2.4		0.5 C	15	900	[23]
				0.8 C	15	800	
				1 C	15	630	
				1.2 C	15	500	
				1.5 C	20	300	

4. Automated test-rig for capacity evaluation of Li-ion batteries

The test rig is designed to calculate the degradation of battery capacity related to battery health. The test rig consists of a lithium polymer battery, charger, voltage sensor, current sensor, temperature sensor, memory unit programmable battery load, and micro-control circuit, as shown in fig (2). The battery is tested with repeated cycles with different load ranges, and the capacity decreases with cycling. The volt, current, and temperature data are saved on memory each second during all cycles. The battery is a lithium polymer battery of 3.7 V,1000 mAH.

The battery is charged with a lithium charger module based on the TP4056 integrated circuit. Charge Li-Ion batteries from onboard Micro USB connector from USB or external +5V source, input voltage: 4.5V~5.5V, fully charged voltage: 4.2V, charging current: 1A adjustable (Set initially to 1A), Working temperature: -10'C~85'C, charging method: Linear charging 1%, Charging precision: 1.5%, The charging has a red indicator light for showing charging process and green light to indicate fully charged. DC voltage sensor based on the principle of the resistor divider, the precision of 0.5%, and a temperature coefficient of 50PPM to ensure detection accuracy effectively.

DC voltage sensor has measurement Accuracy<= 1% and a measurement range of up to 25 VDC. The current sensor (ACS712) measures up to 5A of DC or AC. The ACS712 Low Current Sensor Breakout outputs an analog voltage that varies linearly with sensed current. The Sensitivity of the Current sensor (ACS712): is 185 mV/A. The memory unit module (Micro SD Card Adapter) is a Micro SD card reader module. The SPI interface is via the file system driver and microcontroller system to complete the Micro SD card read and write files. The memory unit module has a level conversion circuit board that can interface level is 5V or 3.3V, the Power supply is 4.5V ~ 5.5V, 3.3V voltage regulator circuit board, and the communication interface is a standard SPI interface.

DC programmable electronic load (ET54) series provides 1mA/10mA high resolution and precision with superior performance. It is equipped with 12 common modes and complete test functions, which can be widely used in a charger, switching power supply, linear power supply, battery, and other production line testing. Overvoltage protection: >150V cut-off input, Overcurrent protection: >40A cut-off input, over power protection: 400W and Over temperature protection: 85°C.

The micro-control circuit figure 2 is designed to control the inputs and outputs of the battery. The test runs automatically and collects data about the memory's current, volt, and temperature. The output data was analyzed with Matlab. For each cycle, plot current, volt, and temperature with time, whether for charging or discharging. The capacity is recorded for each cycle and analysis the degradation during cycling.

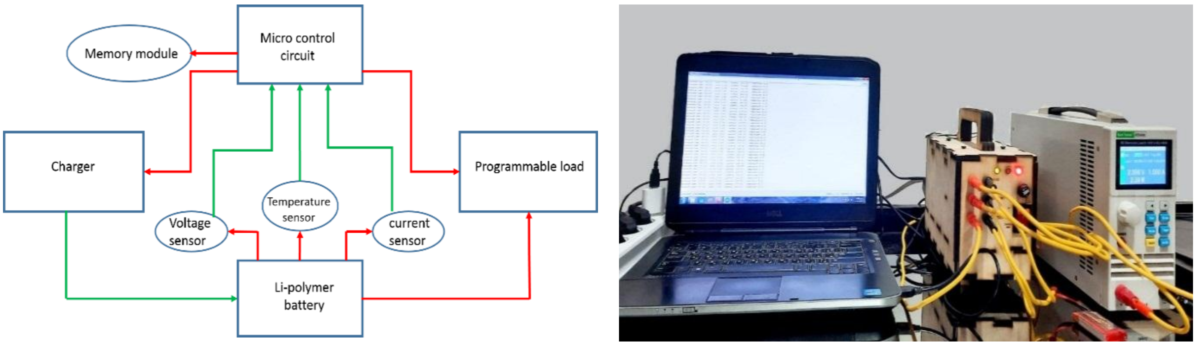

Figure 2. The components of the test rig.

5. Experimental result and analysis

The experiment is about three tests for three batteries under the same condition but with different C-rate. The test is repeating cycles; each cycle consists of charge processing and discharge processing as a following: First, the charging process begins when the battery has 2.8 v &SOC 25%, and the charger feeds the battery with a current of 380 mA until the battery reaches to 4.15& SOC 95%, the current reach to 130 mA at the end of charging process as shown in figure 3.

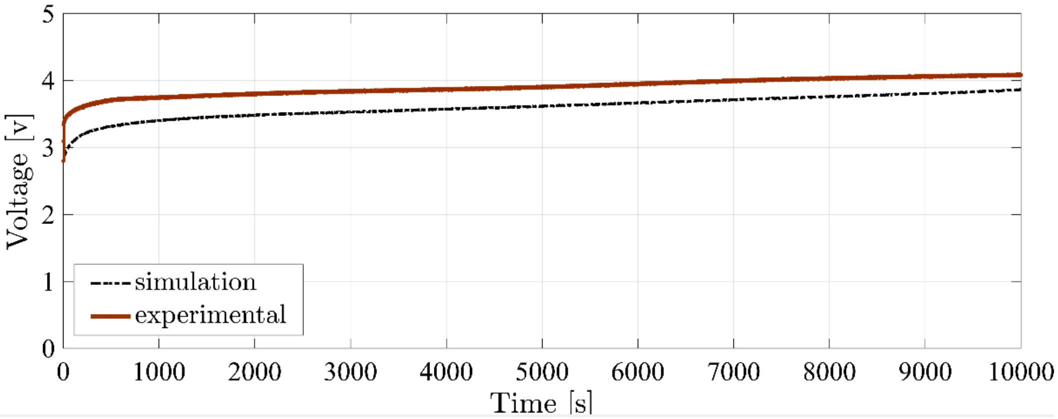

Figure 3. The voltage during the charging process (simulation& experimental).

Second, the discharge process starts with a programmable load after the charging process. The battery discharged with a load with a current value (of 1000mA). The battery throw discharge process starts at 4.15V SOC 90% and reaches the end of discharging process at 2.8 V& SOC 25% figure 4; then the charging process starts, thus repeated until reaching to end of battery life(EOL). EOL estimated with a 20% capacity loss. Figure (5) shows capacity loss throw 200 cycles. The battery aged after 200 cycles by 7 % from the initial capacity. The degradation curve illustrates the tested battery's EOL (20% initial capacity loss) at 580 cycles. Table 6 illustrates a comparison between this study and Goe et al.[23] study.

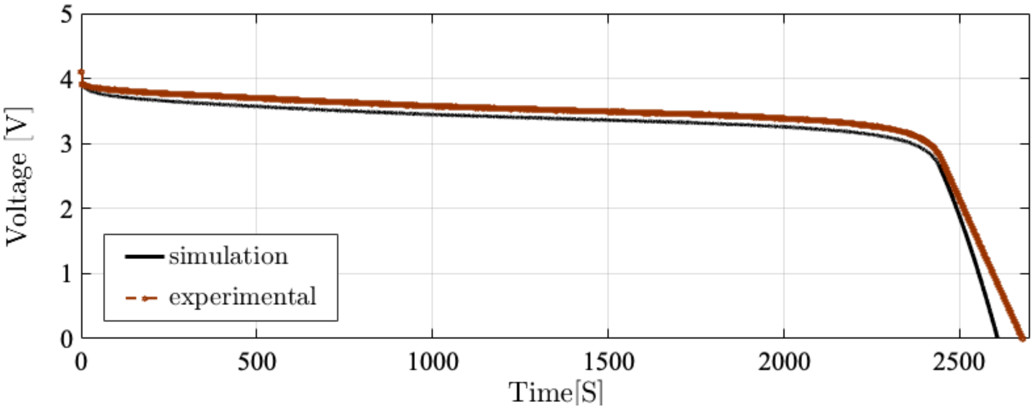

Figure 4. The volt during the discharging process (simulation& experimental).

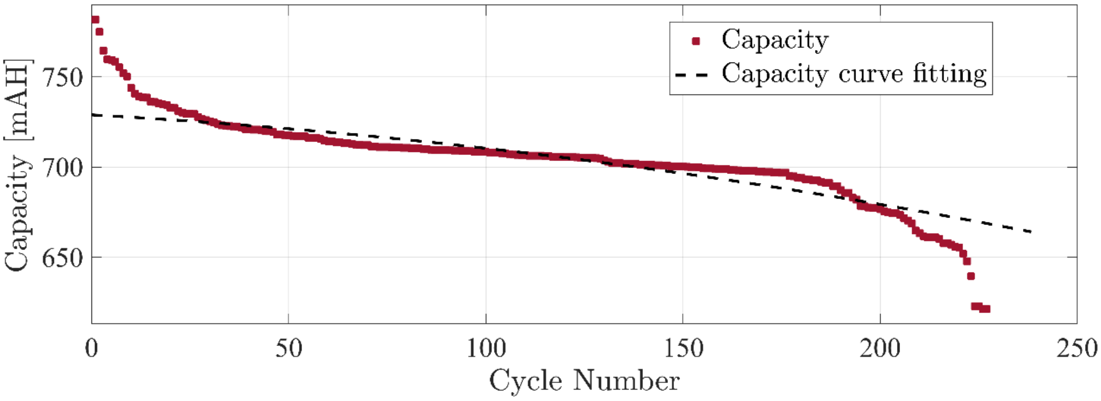

Figure 5. The volt during the discharging process (simulation& experimental)

Finally, the acquired results for battery degradation are illustrated in Figure 5. Such results reveal the fading mechanism of cell capacity after the repetitive charging-discharging process. The obtained results can be used, as shown in the figure to develop empirical degradation models using curve-fitting tools or other sophisticated machine learning approaches to anticipate out-of-range degradation processes of vehicular energy sources and hence, enable efficient battery management decisions.

Table 6:Acomparison between this study and Goe et al.[23] study.

Comparison items	This study	Goe et al[23]
Cell characteristics	730mAH Flat(Pouch) lipo	2400mAh 18650, LCO/graphite
C-rate	1.35 C	1.2 C
Capacity loss [%]	7	15
Test period [cycles]	200	500

6. Conclusion

This paper presented an experimental method for monitoring, evaluating, and assessment of the capacity degradation process in the Li-ion battery. The behavior of battery degradation is complex, so the experimental tests of the battery have structural difficulties. The proposed test rig facilitated monitoring and collecting the battery voltage, current, and temperature data every second and automatically saved the data in the memory module. This Experimental assessment allowed easy data processing and accurate results of battery degradation behavior. This experimental work will present the degradation behavior for the different c-rate patterns. This test rig also allowed testing of the degradation based on the depth of discharge, which can have proposed in a future study.

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