Fast Charging Thermal Management of Lithium ion battery (using silicon oil as a direct contact cooling at different charge-discharge conditions), applications and future prospects of lithium battery system for bio-medical devices (pacemaker, electric-wheelchair)

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This is to certify that the research work presented in this thesis, entitled "…Fast Charging Thermal management of Lithium ion battery (using silicon oil as a direct contact cooling at different charge-discharge conditions), applications and future prospects of lithium battery system for bio-medical devices(pacemaker, electric-wheelchair)" was conducted by Mr. Muhammad Mahad under the supervision of Dr. Shahbaz Khan.

No part of this thesis has been submitted anywhere else for any other degree. This thesis is submitted to the BME, SMME in partial fulfillment of the requirements for the degree of Master of Science in Field of ……Master of Biomedical Engineering
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This thesis is dedicated to my mentor, whose guidance and encouragement have been invaluable throughout this journey.

To my parents, whose unwavering support and belief in me have been my greatest source of strength.

Thank you for your love, patience, and inspiration.

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LIST OF SYMBOLS, ABBREVIATIONS AND ACRONYMS

BMD	Biomedical Device
IMD	Implantable Medical Device
LIB	Lithium Ion Battery
ECG	Electrocardiogram
EGG	Electroencephalogram
DBS	Brain Stimulators
ICD	Implantable Cardioverter Defibrillator
FDA	Federal Drug Regulation Authority

ABSTRACT

Lithium-ion batteries (LIBs) are the central source of energy storage for a myriad of devices, from small medical electronics to larger portable devices. They find their applications in implantable devices within the healthcare system. However, thermal management of LIBs remains a critical challenge, particularly under higher charge-discharge conditions. To address this issue, intensive research is being conducted. This thesis employs the method of direct contact liquid cooling of LIBs to control their temperature within safe operating conditions. The thermal analysis of LIBs evaluates cooling with or without an externally powered cooling system to enhance the performance and safety of LIBs, effectively increasing their life cycle. The experimental setup involves immersing a standard commercial LIB in silicon oil, which is circulated and cooled using an external pump, radiator, and fan before being circulated back to the LIB chamber. The results show significant improvements in the thermal stability of LIBs with this method and the peak temperature values indicate higher thermal cooling, stability, and safety. Thermal management of lithium-ion batteries in medical devices, along with the applications and future prospects of lithium battery systems, are the core topics of this thesis. LIBs are the most effective and ideal power storage systems and have found applications in various portable electronic medical devices such as electric wheelchairs. These medical portable devices use batteries for their portability, providing a range of movement and power backup during emergencies. This research also recommends the future of LIBs in the medical industry and lays the foundation for thermal analysis groundwork for future research.

Keywords: Summary; Thermal Analysis, Lithium-ion battery (LIB), Medical devices, Direct contact cooling, Fast charging-discharging.

CHAPTER 1: INTRODUCTION

This is an era of technological advancement and new inventions are in the making or in the market. These advancements have increased the demand of electrochemical energy storage because of their many new systems demands different types of the energy storage and they provide this versatility[9], [10]. Lithium-ion battery has distinguished itself as an electrochemical storage and founds it applications in many devices like ventilator, oximeters, electric-wheelchair and many more. LIBs provide versatility according to the situations and it mainly important because of its higher energy density and longer life especially in case of implantable medical devices as the replacement of the device or battery through operations is neither cost effective nor can provide comfort to the patient[11].

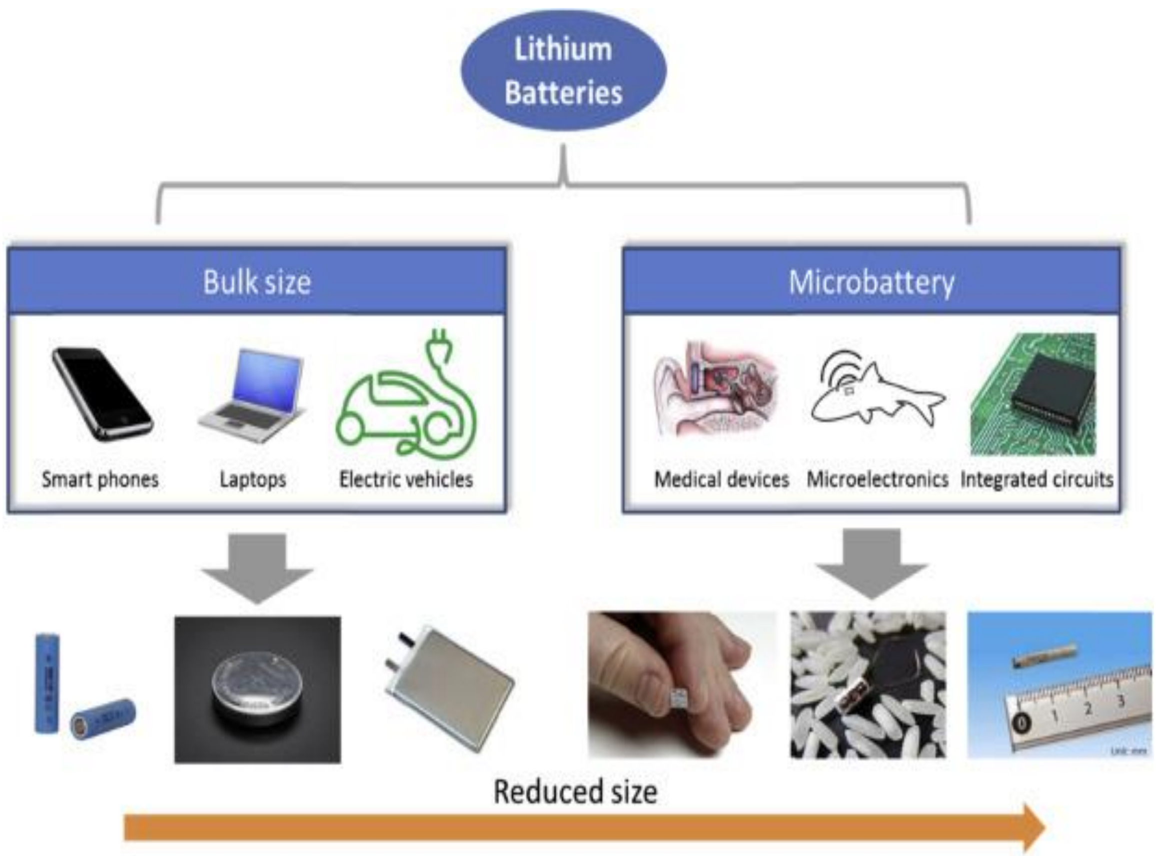

Figure 1: The applications of LIB in the medical and electronic technology[12].

The pressure of global warming and pollution as a result of the burning of fossil fuel has pointed the importance of electric vehicles and the like equipment the need large storage capacity. The main component of an EV is battery or energy storage which will determine the major cost of production of the vehicle. The batteries which were in use of the fossil fuel driven vehicle and equipment are lead acid battery, the main purpose of the use of this type of battery is just to start the engine for the first time and then the vehicle will become self-sufficient and will not require battery for it operations there for less efficient, having lower life cycle batteries were in use, but due to the large requirement energy storage and frequent use of the battery lead acid battery cannot be used as lead acid battery neither have large capacity nor they can be in used for a longer period. Lead acid battery have lower specific density. LIBs have no memory effect disadvantage in it with helps in the performance. The voltage profile of LIBs is much stable than the conventional lead acid battery and the like. The have the capacity of high discharge which is much needed in the modern electronic which require power out put in either high density or in pules like EV and mobile equipment of the health care center. This high discharge will than require a thermal management system as discharging is an exothermic process which needed much heat to be removed from the battery system or this will lead to different problems of the battery like thermal-runaways or can decrease the life or quality of the battery. Quality of the battery means that it will either behave differently than the battery which runs within the required conditions and will have different power capacity and current and voltage profile. Therefore, thermal management is necessary for LIBs for having long life and capacity. This is also good for the safety of the equipment and the personal in their capacity locations because overheating will lead to the explosion of the battery.

Therefore, keeping all the factors discussed in view it is necessary to develop BTMS that will have a strong capacity to maintain the temperature of the battery to the recommended operating temperature and keep it away from the critical thermal runaway temperature. BTMS usually controls the temperature by removing excess heat from the system an dissipated it into the environment. There is also an important point to be noted that the internal temperatures of the battery mainly LIB are different from the surface temperature and this discrepancy must not be large as this will create problems in the battery and result in the decrease in its capacity. So, gradual cooling is recommended in thermal management. The thermal management of the battery and it cooling are now generally be done by direct and indirect cooing mechanism. Some of them are mini-channel plate cooling, PCM cooling, fan air cooling and heat pipe cooling. The most common cooling is the FAC, in this air is circulated in the battery system from the environment or from the ac duct which is pre-cooled and circulated in the battery to remove the heat from the battery and cool the battery. This system has its advantage as it is easy to installed in the system and it inexpensive and does not mush maintenance but there is an disadvantage to this system is the it is not able to uniformly control the temperature of different cells in the battery which results in that some cells inside of the battery will be at higher temperatures than the other and if this is lasted for a longer period of time than the capacity of the battery will be compromised as some cell will degrade more than the other. The thermal capacity of the air is much less as compare to the liquid this is also the reason why it is not able to remove the heat from the battery, different experiment and improvement have been continuously taking place in the world to increase its heat transfer capacity, some have worked in to increase the density of the gas to increase the heat transfer while works on the design simulation of the battery pack that will give air more direct access to the cells of the battery from battery circulations and heat transfer.

The comparison of the air with the liquid in terms of the thermal capacity and thermal conductivity gives us a better view that liquid have better capacity to remove heat form the cells if they are utilizing than air. The example is water which is a liquid have a tens of time better thermal conductivity capacity then the air. This also means that they will have much better cooing capacity than the air, the air cooling is mush depended on the environmental conditions while liquid also do depend on it butt are better than in heat conductions.

1.1 Lithium-ion-battery:

Lithium-ion-battery provides higher energy density, lower volumetric space, longer life cycle and no memory effect this is why they distinguish itself and be able to be found in almost every electronic device[13], [14], [15]. Cylindrical and prismatic are the two main design of LIBs available in the market and the experiment in this thesis uses cylindrical LIB cell [16], [17].

Battery type	**Recharge ability**	**Cathode material (+)**	**Self-discharge time**	**Safety**	**Application**
Li	Non-rechargeable	I_2, MnO_2, CF_x, SVO, $SoCl_2$	long (10 years)	Risk of thermal runaway	Implantable electronics
Silver oxide	Non-rechargeable	Silver oxide	Long (5–7 years)	Free from thermal runaway, hazardous when ruptured	Ingestible electronics, Capsule endoscopy, insulin pump
Li-ion	Rechargeable	$LiCoO_2$, $LiFePO_4$, $LiMn_xO_y$, $LiNiMnCoO_2$	Long (3 years)	Protection circuit is mandatory, low toxicity	Implantable electronics

Table:1 The different types of battery specifications is compline in the table.[12]

LIB like any other electrochemical battery consists of two main parts; an anode and cathode. These parts as a combine is called electrode, which is separated by a separator. The cathode is composed of metal oxide of lithium while anode is mainly made up of graphite or carbon [7], [9].

Figure 1.1: Lithium ion battery utilization in electric wheel scooter.[1]

1.1.1 Charge-Discharge Cycle of LIB

During charging energy is store in the LIB and in the discharging process the store chemical energy in released and utilized in the form of electrical energy. Lithium ion is deposited in the anode during charging and they move back to cathode during discharging. Both the electrodes are separated by a separator and a non-aqueous solution of salts mainly salts of lithium ions are uses as an electrolyte[16], [18], [19]. The charge-discharge cycle of lithium-ion battery is shown in figure.1.

The comparison of the air with the liquid in terms of the thermal capacity and thermal conductivity gives us a better view that liquid have better capacity to remove heat form the cells if they are utilizing than air. The example is water which is a liquid have a tens of time better thermal conductivity capacity then the air. This also means that they will have much better cooing capacity than the air, the air cooling is mush depended on the environmental conditions while liquid also do depend on it butt are better than in heat conductions.

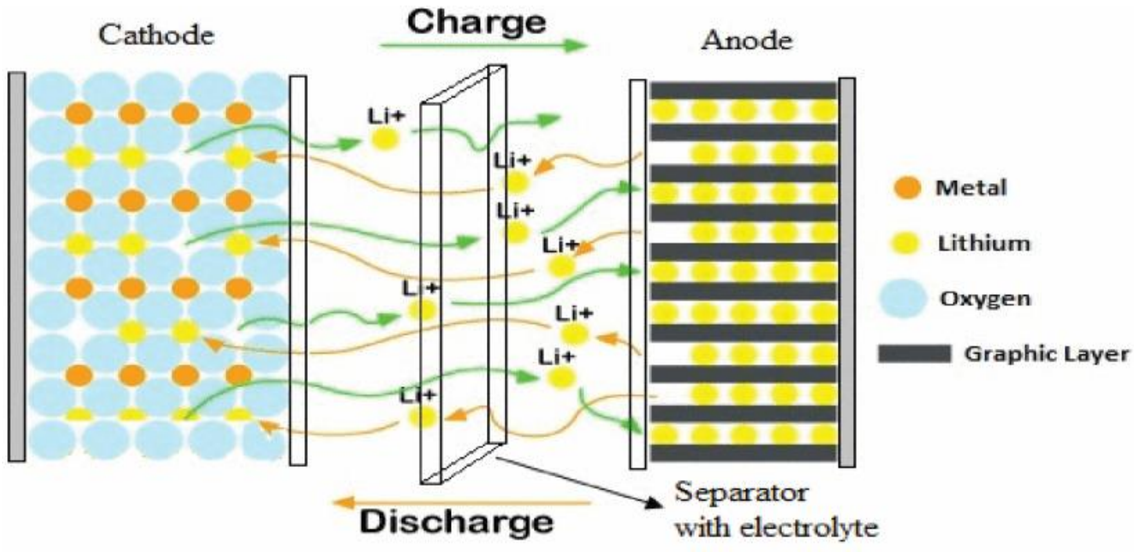

Figure 1.1.1 Charge-Discharge Cycle of LIBs. Reproduce with permission of copyrights 2018 IEEE [17]

1.1.2 Thermodynamics of LIBs

In the charge-discharge cycle of LIBs; charging is endothermic while discharging is exothermic[20] Mainly the charging process is endothermic which means that the temperature of the battery must drop during this process but this is always not happen because heat is produced because of heating effect and this heating effect further increased the temperature of the battery during discharging [11], [21].

1.1.3 Thermal Runaways:

Thermal runaway is a critical problem of LIBs having poor thermal management. This is usually occurred at higher temperatures; this temperature is usually called critical temperature and it depends on the material of composition of electrodes [13]. When the critical temperature reaches because of the poor thermal management the separator between the electrodes melts this results in the chain reaction in which battery discharges within few secs and temperatures rises uncontrollably which results in catching fire or combustion of the battery. Battery receives an irreplaceable damage and this also damages the electronic devices which it is attached to it because of either fire or blast. An example is lithium phosphate battery in which usually battery face thermal runaway in between 100-150 ^{0}C [22], [23], [24].

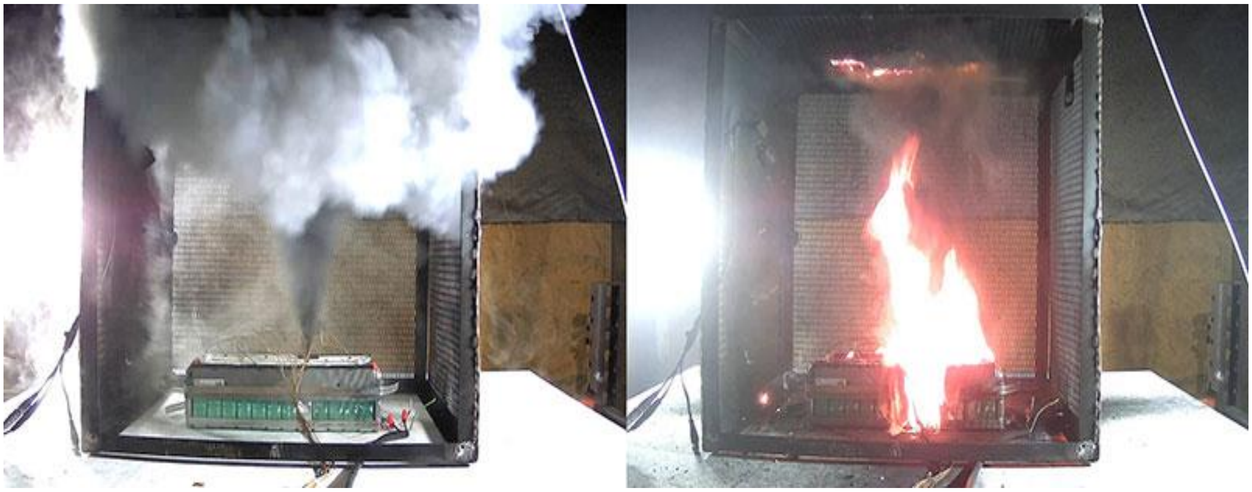

Figure 1.1.3: Thermal runaway is shown in the figure [2].

1.1.4 Thermal management:

The risks of thermal runaway make it necessary for LIBs to have an effective thermal management especially for high performance health of the battery. This will insure the safety of its use in the operations. The methods that are usually use for the thermal management are air cooling and liquid cooling. The selection of method to employ depends on the applications of utility[21] . Novac fluids are better options butt have phase change material which will require more sophisticated equipment handing and this will require in higher cost of the battery [25]. Failure to thermally manage the Lithium ion battery is show, ones the one cell thermally fails than the whole battery pack will fail and it will as a whole catch fire.

Figure 1.1.4: Failure to thermally manage the Lithium ion battery is show, ones the one cell thermally fails than the whole battery pack will fail and it will as a whole catch fire[3].

1.1.5 Liquid Cooling

Direct and indirect liquid cooling are the two major types of cooling to be employed in the cooling of the battery. In the direct types, coolant is in direct contact with the cell while in the indirect type coolant will not be in direct contact of the cell. Direct type provides more area of contact which results in better thermal cooling [26]. There are many types of coolants available for cooling fir the direct contact cooling like mineral oil, and Novac fluids. Novac fluids are better options butt have phase change material which will require more sophisticated equipment handing and this will require in higher cost of the battery [25].

The comparison of the air with the liquid in terms of the thermal capacity and thermal conductivity gives us a better view that liquid have better capacity to remove heat form the cells if they are utilizing than air. The example is water which is a liquid have a tens of time better thermal conductivity capacity then the air. This also means that they will have much better cooing capacity than the air, the air cooling is mush depended on the environmental conditions while liquid also do depend on it butt are better than in heat conductions.

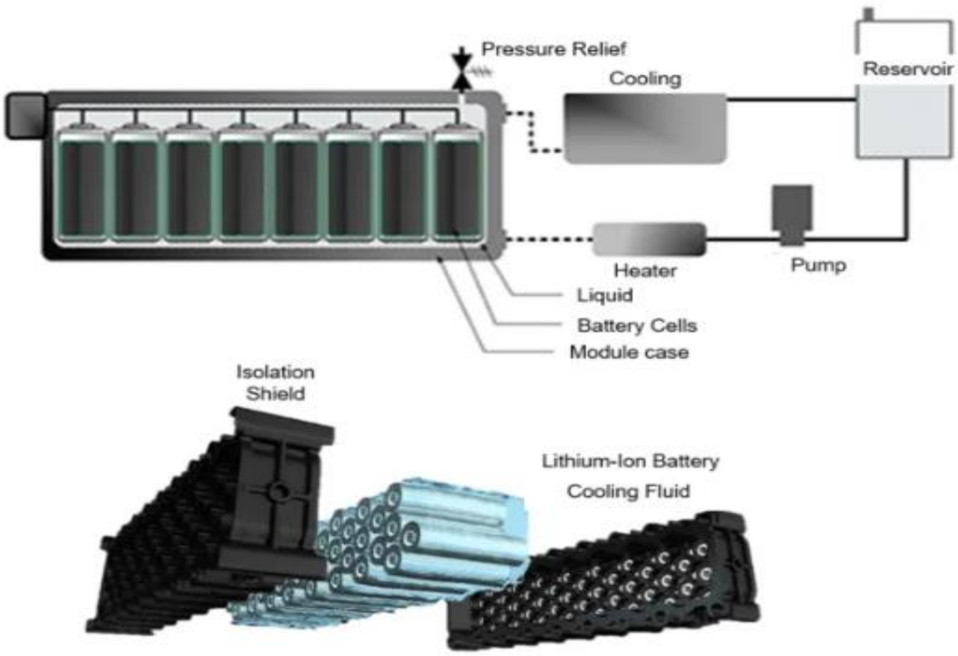

Figure 1.1.5: Liquid Cooling mechanism is shown in the figure for lithium ion battery pack for the cylindrical cell[4].

1.1.6 Biomedical Device

Biomedical devices are objects that helps in improving the human life. They are used to record vital information, monitor, or correct the defective part of the body that need some assistance for working seamlessly. They extend the life of the part that need assistance and directly improve the human life. The part of the body could be any mussel, organ or any neurological system that is the part of the body[12].

1.1.7 Implantable Biomedical Device's Batteries:

Implantable biomedical devices are surgically implanted in the body. IMDs depending on the application they may require power for their normal working like cardiac pacemaker, neurotransmulator, cochlear implants, among others. The requirement of power is not a necessity for every IMDs like stents, hip and knee implant, among other; but those that require them will not work without power. IMDs are selected primarily for size, longevity constraints, this is mostly because the longer life increase the size of the battery and the IMDs. The batteries of IBMs occupy 25-60% by volume. The energy source of IMBs are either primary source battery or passive energy harvesting.[27]. The ongoing research in the medical devices, energy source and battery technology has successfully reduced the size of the medical devices significantly by improving the technology, battery energy density, by using secondary source battery and active battery charging through wireless means [28]. There are many challenges that need to be addressed for the IMDs, such they must be biocompatible and the other will be depend on the specific application of the IMDs. This has been observed that the most IMDs that required energy for its operation need high electrical or chemical energy and the source must be stable and easily accessible. Therefore, after studying many battery systems it is has been found that Lithium Base batteries are one of the best options for IMDs. [29]

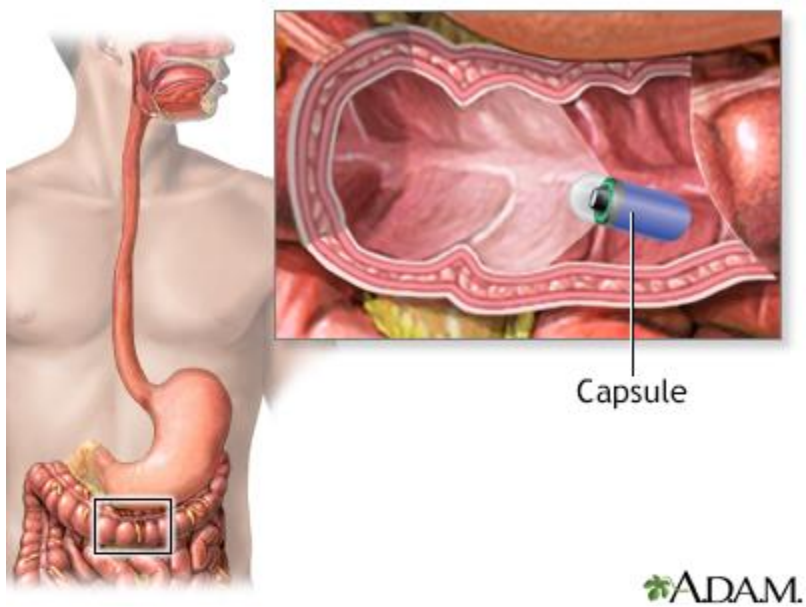

Figure 1.1.7(a): Shown the endoscopy capsule working[5].

This new technological era has increased the life expectancy by providing access to high quality healthcare system which directly increase the quality and quantity of life[30]. This increased life expectancy results in prevalence of aliments like cardiovascular diseases, diabetes, dementia [31] Only in America about 60 % adult's population are in some form of chronic diseases like; diabetes, heart diseases, stock, cancer.[32] Around 27% or 1 in 4 people have some form of disability in United States and they are going to live with it their life[33]. In order to decrease morbidity or increase morality biomedical devices play their role. Around the world about 3 million cardiac pacemaker and 600000 installed annually[34]. Around 0.75 million cochlear implants are installed and people are living with them[35]. The biomedical devices provide support for the defect in the human body so that it runs more normally and independently. The major problem with the biomedical device is their energy source. Energy requirement is dependent of its functions and complexity of the devices, the more it provide support and functions than the more energy intensive it will be. This paper discusses the energy support for the biomedical devices. The biomedical devices are categorized according to their function and applications as; therapeutics, diagnostics and closed loop.

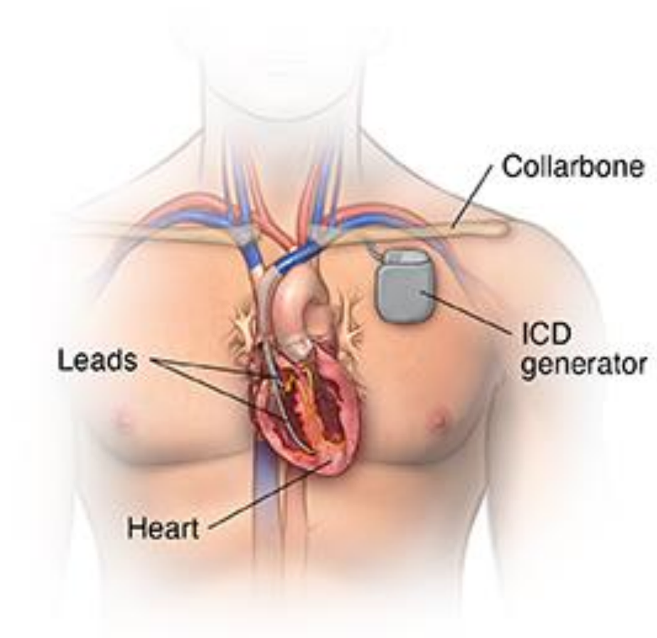

Figure 1.1.7 (b): ICD pacemaker is installed to the heart and leads is shown.[36]

The devices that are used to monitor the existing medical conditions and on the basics of which medical person are able to better understand the underlying condition of the diseases are called diagnostic devices. These devices can also save the data for an extended period of time. This clinical data will help for more accurate diagnoses and progress. Diagnostic devices help medical person for the treatment. Some examples are EEG, ECG, endoscopy.

Therapeutic devices are involved in the medical intervention. These devices are used for the treatment of the particular diseases like neurostimulator is used for as a pain reliver. Some example is; deep brain stimulator, wireless capsule endoscopy.

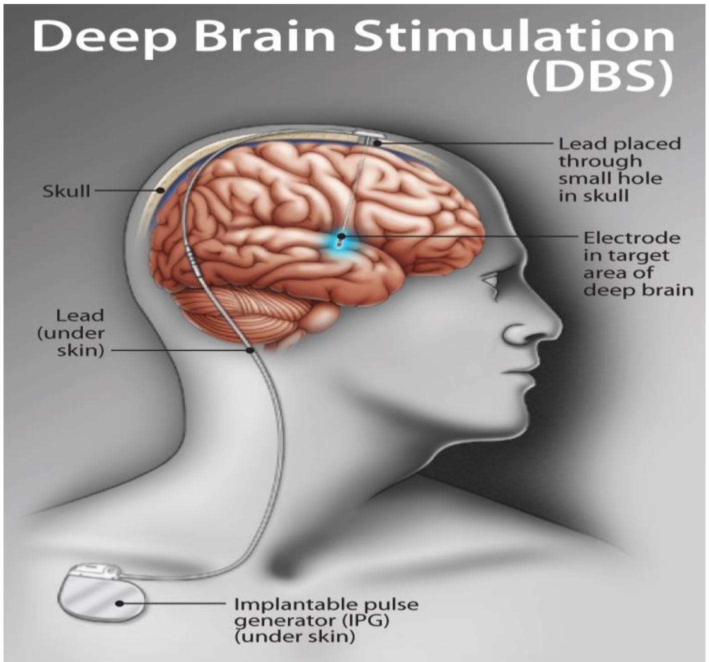

Figure 1.1.7 (c): Deep Brain Stimulator is shown is the figure[6] .

For the better treatment both diagnostic and therapeutic treatment is combined in closed-loop system. In close-loop system sensor are used to monitor and save the data from the biomarker for the disease and then this data is process and the treatment is adjusted accordingly. Example for this system can be found in pacemaker for the treatment of cardiac arrhymia and deep brain stimulators (DBS). Some example are pacemaker, ICD and cochlear implant [15]

1.1.8 Power Requirement for biomedical device

The vast technological development that happen in the last decade had help in the development of medical devices and procedure. There are many new features had been added in the medical devices like wireless interface which makes it more user friendly, and also relevant surgical procedure has been introduced and performed clinically which help's in the installation of the device and cause least discomfort and rapid healing. The use of technology with more added features not only made the medical device safer but this has also increased the power requirement for the device. The gathering of data from the biomarker and the analysis and processing of this data that involves artificial intelligence and decision making, has resulted in the constantly increasing power requirement. Table 1.1.8 shows some of the implantable medical devices power requirement.

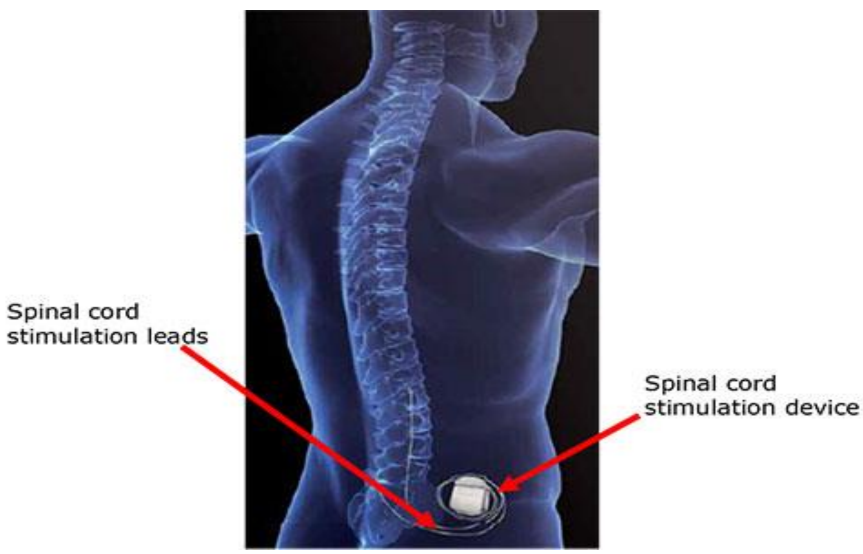

Figure 1.1.8: Spinal cord Stimulator is shown in the figure and its locations of implant[37].

Device	Power Requirement
DBS	100 μ W
Spinal cord Stimulator	1–10 mW
Pacemaker	10–30 μ W
ICD	50–500 μ W
Wireless capsule endoscope	5–30 mW

Table 2.1.8 shows some example of power requirement of biomedical devices

1.2 Types of Lithium ion battery:

Lithium ion battery made from different materials other than the common material use like lithium ion in the form of solid metal or salts like sulfate and nitrates of lithium is categorized as different types of the lithium ion battery because they are made up of different materials. Usually the lithium ion battery used in the system and that are available for the use in the industrial market are the fallowing types of lithium ion battery.

1.2.1 Lithium Cobalt Oxide

Lithium cobalt oxide also written as LiCOO or LCO. In this annotation L represent lithium and C represents cobalt and O represents oxygen. Lithium cobalt oxide battery has high specific energy capacity and thus make it more useful for more energy dense applications and mobile applications. Some of the applications of LCO are digital camera, laptops battery and mobile battery are also made up of this type of battery. Like every battery this also have an electrode and cathode the cathode is made up of cobalt oxide and the anode is made up of graphite oxide. The cathode is layered structured like every other lithium ion battery and lithium ions move from anode to the cathode in the discharging phase and vis versa as the flow reverse on the charge. There are advantages of used this type of battery like the higher energy density than there are also disadvantages in using it like lower thermal stability and lower life cycle and this also have limited load bearing capacity. The following figure shows the layering of lithium ion battery of LCO[7].

The few disadvantages that are observed in this type of battery are usually short life span. Low thermal stability and the lower specific power. Like other battery of cobalt metal lithium cobalt battery also have an anode of graphite which in than limit the cycle life of the battery by changing SEI of the battery. The thickening of solid electrolyte interface on the side of anode and lithium deposition when the charge g rates are higher and the weather temperature is lower. To resolve theses drawback different other metals are used like nickel, manganese and aluminum to improve the load bearing capacity and longevity of the battery and to decrease the cost and make it more economical.

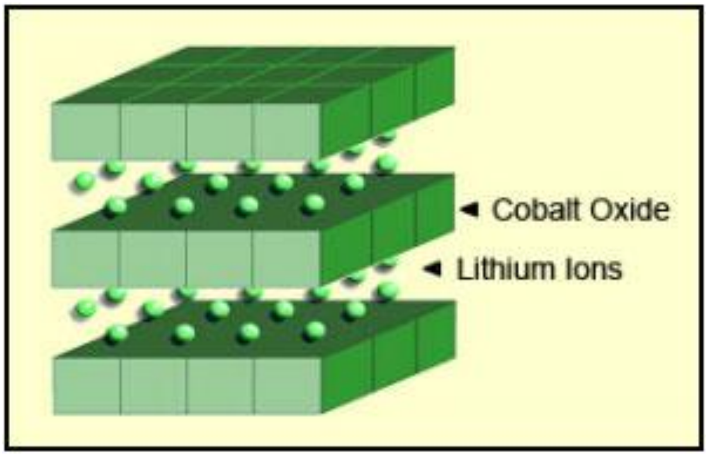

Figure 1.2.1(a): Li-cobalt structure, the cathode are in layers, lithium ion moves from anode to cathode on discharge and from cathode to anode during charge[7]

Lithium combat battery are not recommended to be charged at higher rate of C. This is also recommended to be charged are 1-C rating or 0.8 C-rating. This is to make it clear that there’s no confusion that the c- rating is different for every battery. For example, a battery of 2000 mAh and the battery of 4000mAh of 21700 type of the battery have different currents for different c rating for 2000 mAh battery 1C rating means 2000mA current and for 4000 mAh battery this means 4000mA. So lithium cobalt are charges at lower charging rating. So, it is always recommended to use battery protection circuit for control c-rates.

This hexagonal diagram summarizes the performance of lithium cobalt battery. As it has been discussed that LCO batteries performs best in terms of the specific energy as it store more energy in it as compare to the other types of the battery and have higher energy density but its performance in the sector of life cycle is not good as it has not may cycle as it is energy dense but thermally unstable which in it itself note the problem of safety[7].

Some of the properties of lithium cobalt battery are as the following; the nominal voltage is 3.6 volt and the operating voltage of the battery is usually between 3 to 4.3 volts. The specific energy capacity of the LCO is usually in the range of 150-200 Wh/kg and it been observed as high to 240 Wh/kg. this is usually charged at around the c rates of lower rates and recommended to be charged at 0.7-1C charged rated.

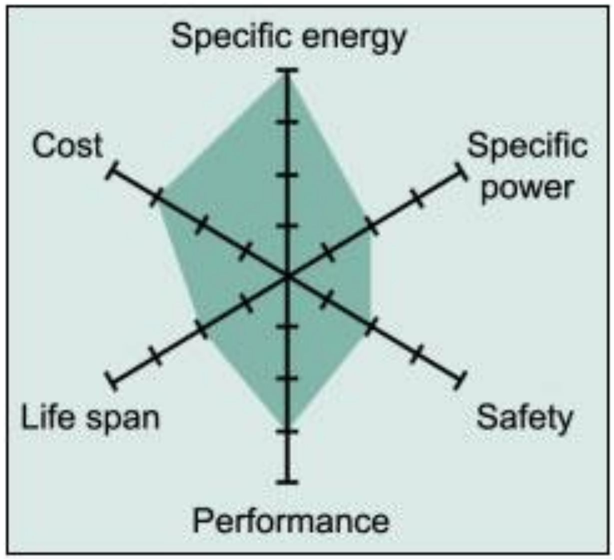

Figure 1.2.1(b): graphical representation of the properties of LCO battery; it performance batter in specific energy and worse in specific power, safety and life span.[7]

The cutoff voltages of LCO are usually 2.5 volts in the lower extreme and 4.2 in the higher extreme and the cutoff current for the charging is at 0.05C rate. As it is charged at lower charged rates this type of battery usually takes about 3 hours to be fully charges. The life cycle of the battery are not on the higher side and it highly depend on the use of the battery application butt it has a usually 500-1000 life cycle. The life cycle highly depends on the environment, use temperature, load and depth of discharge. Thermal runways occur at 150^0C so temperature of LCO must be control so that it does not reaches that limit.[7]

1.2.2 Lithium Manganese Oxide:

Lithium manganese oxide are also called LMO battery. Lithium ion battery utilize different metals in the cathode and manganese is one of them. It has been about three decades that lithium ion battery uses manganese in the cathode formation. The manganese used in the spiral form in the three dimentional from and this improved the flow of the electrons on th electrode thus help in the lower resistance internally and improves the current flow in the battery. Thus helps in the thermal stability as the internal resistance is lower lower heat will be produced. Thus high thermal stability and enhanced safety and have limited life cycle.

This battery have the ability to charges at higher c-rates as it is thermally stable as compare to the LCO battery. This is because of the low internal resistance which helps in the better flow of the current and does not built an additional heat in the battery which destabilized the whole battery. It has the capacity of continuous discharge current of 20 to 30 ampere and the current in pulses form in around the range of 50 Ampere with the moderate generation of heat. The thermal runaways of this battery is around 80 degree and the temperature must not be built and must be removed with the BMS system. They are usually found in medical instruments, power tools and in EV[7]

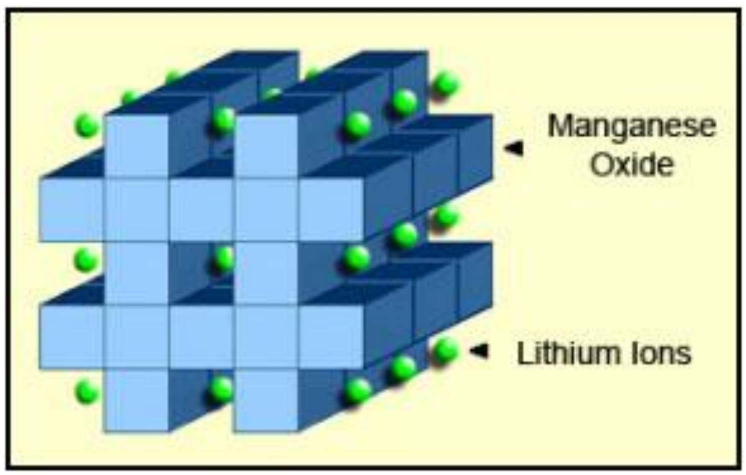

Figure 1.2.2(a): the spiral structure of LMO cathode and its three-dimensional structure[7]

The capacity of LMO is on the lower side and it is less than the half of the capacity of LCO, but the it has longer life span because of its design flexibility. It has the maximum load current bearing capacity and can be charged at higher rates. For example and cell of 18650 having the capacity of 1000mah of LCO and LMO than LCO cell will be of small size than LMO but LMO will be able to be charge in the shorter period of time and will be able to bear the load of higher power requirement machinery.

The following figure shows the specific properties of the LMO battery and it applications. The characteristics appears average but this has increased the safety and life span of the battery considerably.[7]

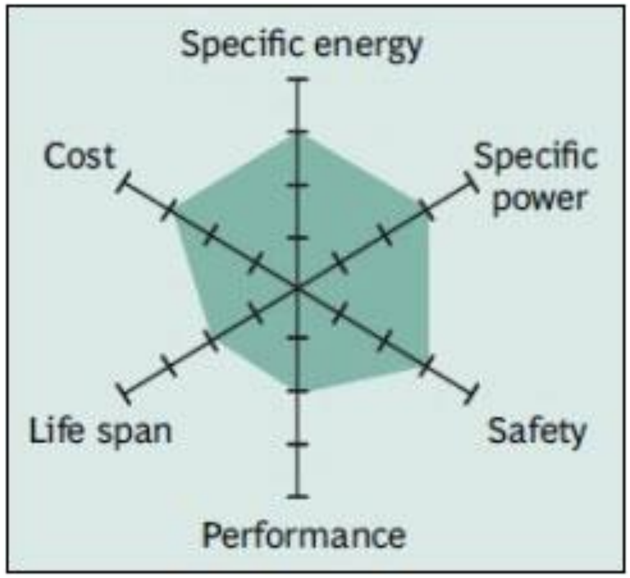

Figure 1.2.2(b): the overall performance is average on all side butt there is a considerably improvement in the safety and longevity of the battery. The specific power of the battery also increased and now able to support the higher energy equipment.[7]

Most of the lithium manganese batteries not only bled lithium and manganese but it also blends nickel and cobalt in it to improve its specific energy and life span. Therefor LMO and NMC are used for EV and the application of large output energy requirement. Usually the battery are made of different parts, in one battery NMC and LMO both are used one give higher specific out and the other give longer range and life.

The research on the lithium ion battery revolves around the blends of lithium. Nickel, aluminum, manganese and cobalt as the main or only cathode materials thery are mainly uses in the oxide form or another form of salts. Silicone can also be added which can give a capacity boost but can short the life span of the battery as continuous charge and discharge produce mechanical stress in it. The use of silicone and three metal Li, Mg and Co can enhance the capacity and longevity of the battery in different proportion. The requirement of the battery is different for the industrial or home devices.

The specific properties of the LMO battery are the flowing. The nominal voltage is 3.7 v and the typical operating voltage is 3 to 4.2 v per cell of the LMO battery. The specific energy capacity is 100-15- Wh/kg. the recommended charging capacity rate is 0.7 to 1 C but it has the capacity to be charged at higher rates at 3C. the maximum cutoff voltage is 4.3 v and the cutoff current for the charge is 0.05C. it has the higher discharge capacity of current and goes up to 10 C from 1C and the minimum cutoff voltage is set at 2.5V. it has an average life cycle of able 300-700 and it highly depends on the environmental conditions, use conditions and the depth of discharge and temperature control. The thermal runaways occurs at 250 degree which make it a highly stable and this is because it found its applications in power tools, medical devices and the electric vehicles.[7]

1.2.3 Lithium Nickel Manganese Cobalt Oxide:

Lithium nickel manganese cobalt oxide battery are one of the most use battery in the world because of it dynamic properties. are also called NMC battery. Lithium ion battery utilize different metals in the cathode and manganese is one of them. It has been about three decades that lithium ion battery uses manganese in the cathode formation. The manganese used in the spiral form in the three dimensional from and this improved the flow of the electrons on the electrode thus help in the lower resistance internally and improves the current flow in the battery. Thus, helps in the thermal stability as the internal resistance is lower heat will be produced. Thus, high thermal stability and enhanced safety and have limited life cycle.

Higher power and longer life find its applications in the electric bikes, medical devices and power trains. NMC used different concentration of Ni, Mg and Co and this ratio will change the property of the battery.

This battery has the ability to charges at higher c-rates as it is thermally stable as compare to the LCO battery. This is because of the low internal resistance which helps in the better flow of the current and does not built an additional heat in the battery which destabilized the whole battery. It has the capacity of continuous discharge current of 20 to 30 ampere and the current in pulses form in around the range of 50 Ampere with the moderate generation of heat. The thermal runaways of this battery are around 80 degree and the temperature must not be built and must be removed with the BMS system. They are usually found in medical instruments, power tools and in EV

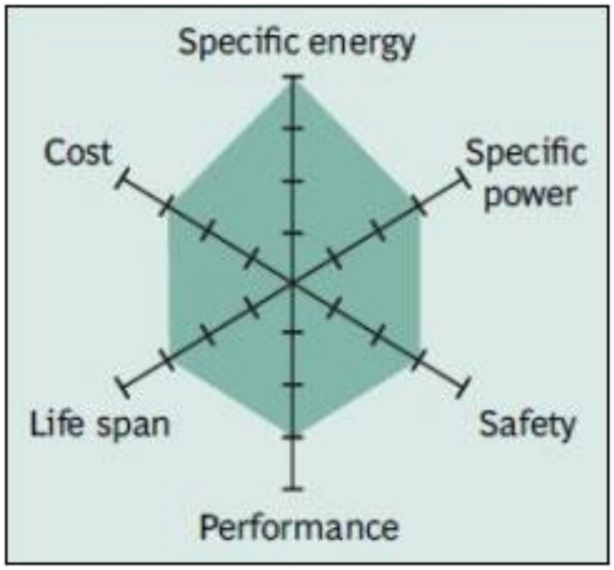

Figure: 1.2.3: NMC has excellent performance in all the sectors, have higher specific energy and safety and longer life cycle.[7]

Most of the lithium manganese batteries not only bled lithium and manganese but it also blends nickel and cobalt in it to improve its specific energy and life span. Therefor LMO and NMC are used for EV and the application of large output energy requirement. Usually the batteries are made of different parts, in one battery NMC and LMO both are used one give higher specific out and the other give longer range and life.

The research on the lithium ion battery revolves around the blends of lithium. Nickel, aluminum, manganese and cobalt as the main or only cathode materials thery are mainly uses in the oxide form or another form of salts. Silicone can also be added which can give a capacity boost but can short the life span of the battery as continuous charge and discharge produce mechanical stress in it. The use of silicone and three metal Li, Mg and Co can enhance the capacity and longevity of the battery in different proportion. The requirement of the battery is different for the industrial or home devices.

The specific properties of the LMO battery are the flowing. The nominal voltage is 3.7 v and the typical operating voltage is 3 to 4.2 v per cell of the LMO battery. The specific energy capacity is 150-220 Wh/kg. the recommended charging capacity rate is 0.7 to 1 C. the maximum cutoff voltage is 4.3 v and the cutoff current for the charge is 0.05C. it has the higher discharge capacity of current and goes up to 10 C from 1C and the minimum cutoff voltage is set at 2.5V. it has an average life cycle of able 1000-2000 and it highly depends on the environmental conditions, use conditions and the depth of discharge and temperature control. The thermal runaways occur at 250 degree which make it a highly stable and this is because it found its applications in power tools, medical devices and the electric vehicles.

NMC with different ration of the three metal gives different properties and this in terms grows the family and diversify the properties of the NMC. The longer life cycle has made it utility in many applications like bike, EV industry any especially in medical devices.[7]

1.2.4 Lithium Iron Phosphate:

This is also is also known as LFP. One of the most used LIB in the world. Lithium nickel manganese cobalt oxide battery are one of the most use battery in the world because of it dynamic properties. are also called LFP battery. Lithium ion battery utilize different metals in the cathode and manganese is one of them. It has been about three decades that lithium ion battery uses manganese in the cathode formation. The manganese used in the spiral form in the three dimensional from and this improved the flow of the electrons on the electrode thus help in the lower resistance internally and improves the current flow in the battery. Thus, helps in the thermal stability as the internal resistance is lower heat will be produced. Thus, high thermal stability and enhanced safety and have limited life cycle.

Higher power and longer life find its applications in the electric bikes, medical devices and power trains. LFP used different concentration of Ni, Mg and Co and this ratio will change the property of the battery.

This battery has the ability to charges at higher c-rates as it is thermally stable as compare to the LFP battery. This is because of the low internal resistance which helps in the better flow of the current and does not built an additional heat in the battery which destabilized the whole battery. It has the capacity of continuous discharge current of 20 to 30 ampere and the current in pulses form in around the range of 50 Ampere with the moderate generation of heat. The thermal runaways of this battery are around 80 degree and the temperature must not be built and must be removed with the BMS system. They are usually found in medical instruments, power tools and in EV.

Most of the lithium manganese batteries not only bled lithium and manganese but it also blends nickel and cobalt in it to improve its specific energy and life span. Therefor LMO and NMC are used for EV and the application of large output energy requirement. Usually the battery are made of different parts, in one battery NMC and LMO both are used one give higher specific out and the other give longer range and life.

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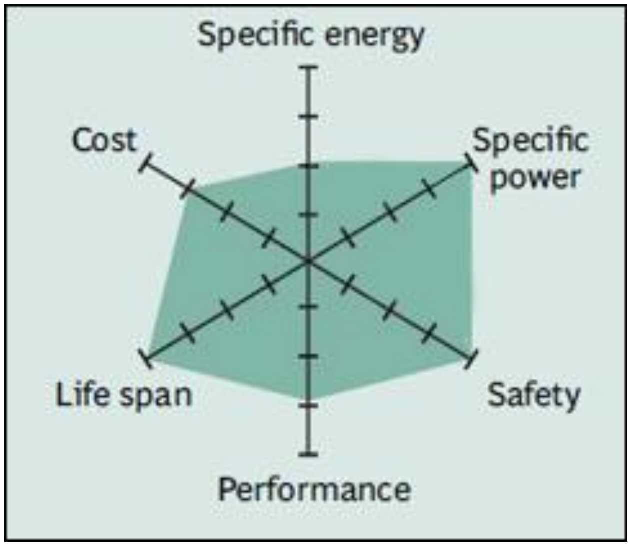

Figure 1.2.4: graphical representation of the properties of LFP battery; it performers better in specific power and worse in specific energy. Safety and life span are its best performers.[7]

LFP has longer life cycle has made it utility in many applications like bike, EV industry any especially in medical devices. It has the higher specific power in the lithium ion battery system so they are found in the applications of the weighted power applications, they are also used in the power backup system.[7].

1.2.5 Lithium Titanate:

Lithium titanate is one of the oldest lithium batteries in use. One of the main features of this battery is it low cost and voltage. In this battery cathode can be any NMC material but the anode is of titinate not the typical graphite material.

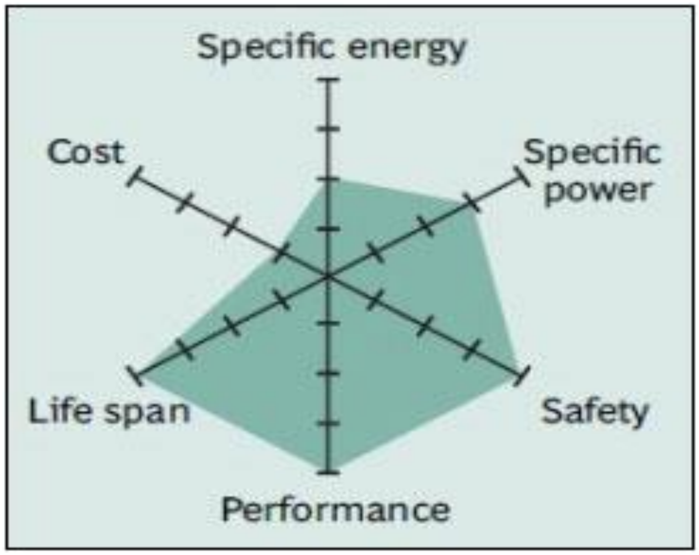

Figure 1.2.5: graphical representation of the properties of LTO battery; it performers better in specific power and worse in specific energy. Safety and life span are its best performers.[7]

The few disadvantages that are observed in this type of battery are usually short life span. Low thermal stability and the lower specific power. Like other battery of cobalt metal lithium cobalt battery also have an anode of graphite which in than limit the cycle life of the battery by changing SEI of the battery. The thickening of solid electrolyte interface on the side of anode and lithium deposition when the charge g rates are higher and the weather temperature is lower. To resolve these drawback different other metals are used like nickel, manganese and aluminum to improve the load bearing capacity and longevity of the battery and to decrease the cost and make it more economical.

Lithium combat battery are not recommended to be charged at higher rate of C. This is also recommended to be charged are 1-C rating or 0.8 C-rating. This is to make it clear that there's no confusion that the c- rating is different for every battery. For example, a battery of 2000 mAh and the battery of 4000mAh of 21700 type of the battery have different currents for different c rating for 2000 mAh battery 1C rating means 2000mA current and for 4000 mAh battery this means 4000mA. So, lithium cobalt are charges at lower charging rating. So, it is always recommended to use battery protection circuit for control c-rates.

This hexagonal diagram summarizes the performance of lithium cobalt battery. As it has been discussed that LCO batteries performs best in terms of the specific energy as it store more energy in it as compare to the other types of the battery and have higher energy density but its performance in the sector of life cycle is not good as it has not may cycle as it is energy dense but thermally unstable which in it itself note the problem of safety.

Some of the properties of lithium cobalt battery are as the following; the nominal voltage is 2.4 volt and the operating voltage of the battery is usually between 1.8-2.85 volts. The specific energy capacity of the LTO is usually in the range of 50-80 Wh/kg. This is usually charged at around the c rates of lower rates and recommended to be charged at 0.7-1C charged rated. The cutoff voltages of LTO are usually 1.8 volts in the lower extreme and 2.85V in the higher extreme and the cutoff current for the charging is at 0.05C rate. As it is charged at lower charged rates this type of battery usually takes about 3 hours to be fully charges. The life cycle of the battery is not on the higher side and it highly depend on the use of the battery application butt it has a usually 3000-7000 life cycle. The life cycle highly depends on the environment, use temperature, load and depth of discharge. Thermal runways occur at higher temperature and it is considering as one of the safest batteries. temperature of LTO must be control so that it does not reaches that limit. Because of the higher life cycle it is found it applications in emergency backup system, EV and medical devices.[7]

1.2.6 Lithium Air:

Lithium-air batteries has a promising advancement in energy storage, and offering significantly higher energy density than compared to current lithium-ion batteries technologies. It is Inspired by zinc-air batteries and fuel cells, but they are different as these batteries utilize a catalytic air cathode that absorbs oxygen, and combined it with an electrolyte and a lithium anode to "breathe" air.

The specific energy of lithium-air batteries is a quite higher at 13 kWh/kg. For comparison, aluminum-air batteries can be used which is another metal-air variant, have a theoretical specific energy of about 8 kWh/kg. but they cannot be achieved in the practical world but only if they could be achieved in practice, metal-air batteries would compare themselves with gasoline, which also has an energy density of approximately 13 kWh/kg. Even achieving a quarter of this energy density wil be an ideal case for , electric motors, which have efficiencies exceeding 90%, could outperform internal combustion engines (ICE) that typically have thermal efficiencies of only 25-30%.

lithium-air batteries gained renewed interest as in the late 2000s because of the advancement in materials science and the produce more efficient batteries for electric vehicles. Depending on the materials used, lithium-air batteries can produce voltages ranging from 1.7 to 3.2 V per cell. Research efforts are underway at institutions such as IBM, MIT, and the University of California to develop this technology further.

Despite their advantages, lithium-air batteries face several problems and have serious disadvantage. One significant issue is the low specific power, particularly at low temperatures. Additionally, air quality presents a challenge, as the oxygen used must be free from pollutants found in urban environments, necessitating filtration. This could lead to complex systems involving compressors, pumps, and filters, which can consume the electricity which the battery has stored of these excess operations.

Another disadvantage is the formation of lithium peroxide films, these creates barriers that impede electron flow and will be leading to a sudden decrease in storage capacity; this phenomenon known as "sudden death syndrome." Further research is taking place to exploring various additives to prevent this film formation. And finally, the most disadvantage is the life span of the battery which is only 50 cycle and further research is going on to increase it.

1.2.7 Lithium Metal:

In the metallic batteries metal lithium or salt lithium is always use. So, Lithium-metal batteries have been in use and is considered a future of storage system technology for rechargeable batteries or secondary source battery. They have higher specific energy and provide higher output power. However, the foremost disadvantage and quite a tricky challenge is the decomposition of lithium metal and this leading to a leading problem of the growth of dendrite and their propagation. These dendrites are quite a headache as they may and will be able to weak and penetrate the separator layer which is responsible for the separation of cathode and anode but because of their production and propagation battery may cause short circuit and may lead to thermal runaway, catching fire and also be lead to combustion blast. So, safety and risk factors are always considered in the metallic batteries especially lithium batteries.

The constant research in the lithium ion battery technology has made many things possible which were not be done previously. The lag in the last two decades research has made the progress of lithium ion battery very much slow but thankfully the progress is catching up. The growth in LIB is the paramount importance for the industrial growth and massive commercialization which were much difficult previously, but the progressive research has changed the dynamics. For example the German manufacturing company in the year of 2010 have made a LIB with the huge capacity of about 300 WH/kg for an electric vehicle but this is not the only thing reported but the large life cycle of about 2500 has also been observed which not only have provided a large lie of the battery but find a reason to further the research and this has resulted in the decrease in the commercialization cost of lithium ion battery and make it in the competitive pricing range.

Now a days the progress have increase such that the battery pack of car manufacuting company named Audi and the model name of the car A2 have installed an battery pack of such capacity that it provides the range of movement of about 450 km on the single charge of the battery pack. This distance is fair enough for electric cars as compare to the gasoline car which also has the capacity of movement in the range of 200 to 500 km for full tank of the gasoline engine. But another problem occurs that the battery pack were start getting heated enough or for any other reasons that it start catching fire and it rises the concern in regards of its safety risks. So, rigorous test has been started to be performing so to remove the risk factors specially filament formation which is elite a risk as it not only causes fire but it also causes an explosion.

Lithium ion battery have higher energy capacity which goes up to 300 Wh/kg , lithium-metal batteries have even more energy density as they does not carry an excess weight of electrolyte and lithium metal batterie are also known as lithium metal batteries. Therefore, lithium base batteries are the highest known energy dense battery. They are also known as secondary source battery as they are rechargeable batteries. For comparison, Tesla's NCA battery in the Model S 85 has a specific energy of 250 Wh/kg, BMW i3's LMO battery stands at 120 Wh/kg, and the Nissan Leaf's similar chemistry has 80 Wh/kg. the reason being at having different energy densities is that they use lithium ion batteries of different types and they also emphasize on and safety and risk and longevity factors.

Research is going on and the researchers are trying to find the solutions to solve this pragmatic problem of the dendrite growth. Different approaches are in use like an option of adding Nano diamonds as an electrolyte additive has been proposed and experimented on. The principal on which this method is proposed and based on is that lithium preferentially deposits onto diamond surfaces that the separate which usually is made up of Aluminum or is salts, this in result will promotes the uniform deposition and in result improve the cycling performance and longevity. The results data shows a stable cycling for 200 hours which is an excellent progress, but this is still not enough and is found to be insufficient for consumer applications. The applications include the mobile, electric vehicle and laptops which require large number cycle in their life of operations which when see that the increase of 200 house in not significant in the long run. Therefore, additional measures are adopted and taken, such as using non-flammable electrolytes, safer electrode materials, and stronger separators that may give additional hours and add cycle to the life of the battery.

Due to the vast technological development in the recent years significant progress is being made in developing lithium-metal anodes, and once this progress has made vast enough progress than the commercialization will not be far enough. The figure below illustrates the energy density of various anode materials when paired with selected cathode materials and gives us a view that anode is also important as the cathode.[7]

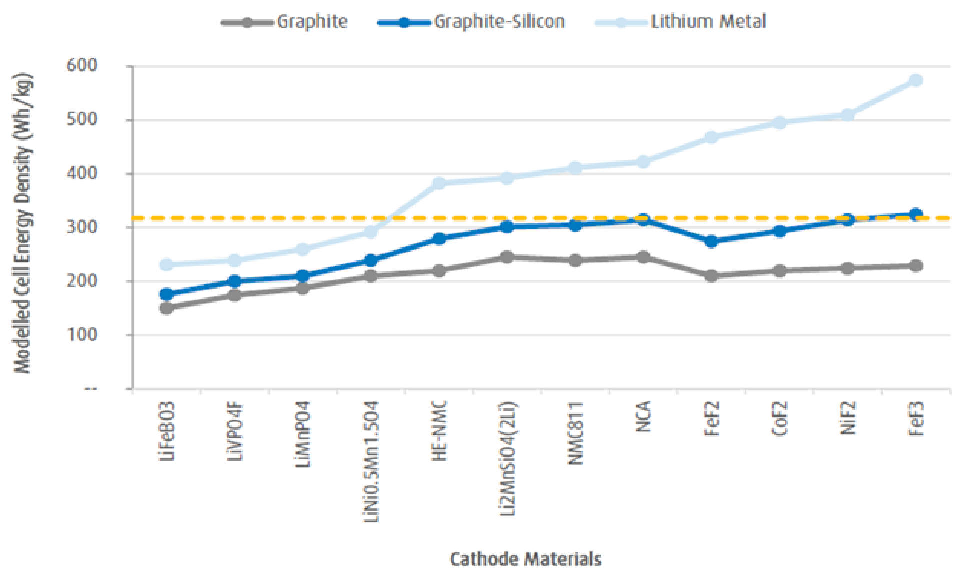

Figure 1.2.7: Cathode material and energy density is shown with the anode material of graphite, graphite-silicone and lithium metal.[7]

1.2.8 Solid-State Lithium:

The last few years of extensive research has resulted on various solid-state electrolytes, including inorganic oxide-based, sulphide-based, polymer, and composite solid electrolytes. Every of each type faces distinct and quite different challenges, and not a single technology has been able to come dominant of every type and therefore, every types of electrolytes are being used.

The conventional Li-ion battery uses a graphite anode, because of its advantages but this limit the scope like which limits specific energy. Therefore, in solid-state batteries graphite is not used as an anode/electrode but in its place pure lithium and the liquid electrolyte is used that also contains a solid polymer or ceramic separator. In the years 1970s lithium-polymer batteries are in used that are now regenerated but at that era they were discontinued due to safety risks and bad performance.

Solid-state batteries have many similarities with lithium-metal batteries, and they also faces the same challenges like the deposition of metallic filament formation, also known as formation of dendrites. They were same as they both uses dry polymer and ceramic separators. Additional challenges also include poor conductivity at low temperatures, difficulty diagnosing problems within the cell, and a lower life cycle count.

The solid-state battery distinguish itself from LIB because it has twice the energy capacity as of standard Li-ion batteries, but it is also observed that solid-state batteries have lower loading capabilities also known as power output because of thermal activity and conductivity of electrolytes, thus making them less suitable for applications that has the requirement of higher output currents, such as electric powertrains and electric vehicle. So, they are more likely to be used for load leveling in renewable energy systems and electric vehicles, capitalizing on short charge times. Researchers are conducting research and they anticipated that as they are now being use as a commercial commodity and is available in the year of 2020, then by the year of 2025 or 2030 they will find their potential implementation in electric vehicles.

The environmentally friendly technology of energy has been able to achive this much is because of the help of governments as they are providing substantial grants for solid-state battery research and tax relaxation. Many research reports highlight that they have high specific energy and they have improved safety risks due to the absence of flammable electrolytes, though some experts remain skeptical and are not much convinced about their viability but the reports show this much. Making the solid-state battery cost effective and more conductive to current and decreasing it internal impedance are the challenges a that are currently working on and ones resolved they be able to stand as comparison of LIB and in cases ca even replace the LIB.

1.2.9 Lithium-Sulfur (Li-S):

Lithium sulfur battery is another lithium ion battery which offer a high specific energy of 550 Wh/kg, which is approximately three times that of standard Li-ion batteries, and a higher specific power of 2.5 kW/kg. the process of discharging is that during discharge, lithium dissolves from the anode surface and deposited in the cathode surface, and this process is reverses when charging. Li-S batteries have a cell voltage of 2.10V, and they perform quite well in cold temperatures, and thus can be recharged at -60°C, and they are favorable in the cold environment. They are also environmentally friendly, with the main component is being sulfur which is being abundant and relatively inexpensive.

Li-S batteries replace the graphite anode with lithium metal. This serves as both an electrode and lithium ion source in the battery thus increasing the concentration of lithium and indirectly increasing the density of the battery. The standard metal oxide cathode in LIB batteries is replaced with cheaper and lighter sulfur, the cost of the standard LIB is mainly depending of the cathode lithium atoms, thus increasing efficiency.

However, Li-S batteries have lower life cycle as they face challenges, including a limited cycle life of 40-50 cycles this is mainly due to sulfur shuttling away from the cathode and reacting with the lithium anode. Researchers have found the solution and be able to increase life cycle of the LI-S battery to 200 cycles. The poor conductivity is due to the degradation of the sulfur cathode over time, and this causes the instability at higher temperatures

1.2.10 Sodium-Ion (Na-ion):

There is another type of battery which is sodium-ion batteries and they are like lithium ion battery but the main metal component in the battery composition is sodium and not lithium. This offer a potential low-cost alternative to Li-ion batteries, as sodium is inexpensive and abundantly available in the earth crest. This is not the new technology but a revival technology it was initially set aside in the late 1980s in favor of lithium, Na-ion batteries have many advantages as they can be completely discharged without the stresses typical of other battery systems, and they can be shipped without adhering to Dangerous Goods Regulations and they do not carry the risk factors of the lithium battery. Some cells achieve 3.6V and a specific energy of about 90 Wh/kg, with lower costs per kWh as their cost can be comparable to lead-acid batteries which is one of the cheapest batteries in the world. Currently like lithium ion battery solidum ion battery is also in highlight and making good progress in making a lower cost effective and longer battery.

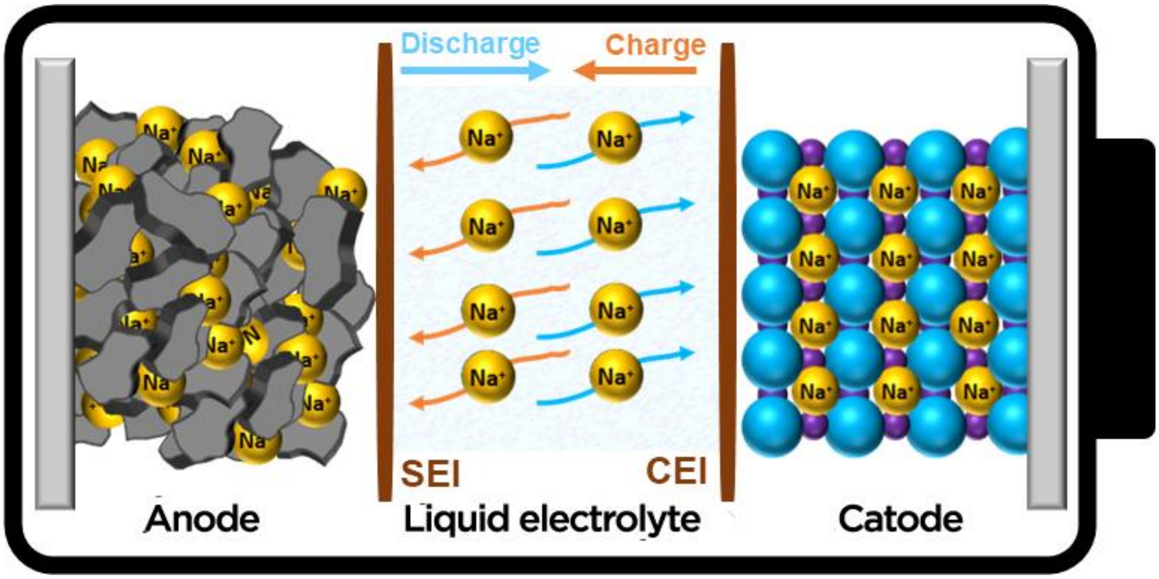

Figure 1.2.10: Sodium ion battery charge-discharge is shown in the figure.[38]

1.2.11 Lithium-Manganese-Iron-Phosphate (LMFP):

One of the longest lives of the battery is Lithium-manganese-iron-phosphate batteries but it does not stop here as they also potentially offer a 15% increase in energy capacity over the traditional LiFePO4 system which is on the higher energy dense LIB system. They also have a potential voltage of 4.0V which is on the higher side, and specific energy of 135 Wh/kg, and a cycle life of around 5,000 cycles. Their economic cost and safety make them suitable candidates for electric intensive devices like electric vehicle, portable medical devices and powertrains.

1.2.12 Dry Battery Electrode:

A battery technology in which a dry battery electrode is used and it could boost Li-ion batteries' specific energy by 50% to 300 Wh/kg, with the potential to reach 500 Wh/kg, while also reducing manufacturing costs. This technology uses the technology of the dry coating method from supercapacitor manufacturing. [7]

CHAPTER 2: IMPLANTABLE BIOMEDICAL DEVICES COMPONENT AND POWER REQUIREMENT

Energy required by any implantable medical device is dependent on its function, complexity and structural component.

2.1 Structural Components and energy requirement.

Biomedical devices are mainly composed of sensors, power unit, actuators, signal processing and control unit, and a data storage unit. Depending on the type of medical device and its complexity some of the not every mentioned part is incorporated in the device.

Generally therapeutic are the least energy intensive and complex device as they required a controlled actuator. It can be controlled in three different ways; by external user wirelessly, by preprogrammed microcontroller, or by external stimuli. While close-loop system has the most complex configurations, as it must contains a sensor, an actuator and a microcontroller. Diagnostic devices have sensors, microcontroller, wireless communication module and on-board memory for data storage and analysis. The size of medical device limits the power unit and some parts that are not necessary to increase the life of the device[39], [40], [41], [42], [43], [44], [45], [46], [47], [48], [49].

2.2 Power Requirement of biomedical devices:

Power requirement of implantable medical devices are often the critical limiting parameter because of the limited available size in the body. Power requirement of many medical devices has been shown in Table 2. Some are not power intensive like pacemaker which required power in micro watts about 10-30 μW therefore they can be remained operational for about 10 years and usually required replacement of battery after every decade[50]. Higher power demand and larger battery sizer are usually balanced with the operational life of the medical devices. Power requirement for artificial urinary splingers (200 μW) and

ICD (50-500 μW) are higher than pacemaker but they also operation life for couple of years[50], [51].

Some medical devices like wireless capsule endoscopy that is used as diagnostic devices they do have larger power requirement of 5–30 mW[52] but due to the limited use they have enough battery or power source for their operation but devices like cochlear implant 100 μW to 10 mW [53] and others that have higher power requirement but limited size to incorporated larger power source and neither their battery can be replaced nonsurgical therefore for these types of the medical devices one primary source battery is not enough to meet their requirement as frequent surgical operations in not economical nor viable as it is more prone to infections. Their battery needs frequent charges and different energy harvesting mechanism or external energy transfer techniques, to charge or extend the power source.[50].

2.3 Batteries to Power Medical Devices:

Since 1958, batteries are the primary source of power for the implantable medical devices and to this day development and advancement has not been stope and it constantly improving the battery characteristics and compatibility.

2.4 Characteristics of Biomedical Batteries:

Batteries are energy storage device that store their energy in the form of electrochemical reactions. The main components of the battery are: an anode, cathode, electrolyte and separator. The materials from which the electrodes (cathode and anode) are made from will define the characteristics of the battery as the electrochemical reactions and all the properties of the battery depends on these reactions. The characteristics parameters for the specific biomedical applications will slightly vary depending on the operation use but for the ideal case that battery should have long life, small in size, be made of biocompatible materials and have no safety risks involved. When selecting a primary source battery, the parameters that are considered are: energy density, energy capacity, nominal voltage, lifetime, discharge profile are important but for secondary source battery life cycle and charge profile is also important characteristics.

Figure 2.4: Battery Powered Medical equipment in the Hospital[8].

The above mentions characteristics are those that are essentially needed for the battery to works as a proper energy source and support the biomedical device for which it is manufactured. Safety of the battery and its ling time stability, biocompatibility are the most important characteristics. Safety and biocompatibility are of paramount importance for implantable devices, if not kept in check these that they can lead to irreplaceable damage and may cause toxicity because of leakage of the battery, or may cause immunogenicity reactions in the body or the explosion of the battery as a whole. Medical device battery safety is very important and they are regulated by the respective government agencies of the country for which they are being used in. Food and Drug Admiration is for United States of America while European Medicine Agency is for European Union, they both regulate medical batteries and have made many rules and standards for the safety and performance of medical batteries and devices.[15]

2.5 Batteries Technologies to Power Biomedical devices:

Since 1958 batteries technology is continuously advancing to meet the requirements. In this section, battery technology, challenges they face and the ways to resolve these challenges are discussed. Biomedical batteries are further classified based on the type of materials they are made from, there operations and further classified on the basis of structure and shape.

There are different types of lithium batteries being manufactured today and they are categories and named by the electrode material they are made from. Two electrodes are used in lithium batteries one is anode which is made of lithium while different set of electrodes are available to be used depending on the characteristic's requirement like lithium iodine (Li/I_2), manganese oxide (Li/MnO_2), carbon mono fluoride (Li/CFx), silver vanadium oxide (Li/SVO) or hybrid cathodes (Li/CFx-SVO). Lithium ion battery being an energy dense battery are more used in medical devices especially in rechargeable applications because of comport to user but the safety factor of lithium batteries is always taken into consideration as being used in implantable device being safe is the compulsory. While lithium-ion battery uses lithium cobalt-oxide ($LiCoO_2$), lithium iron-phosphate ($LiFePO_4$), lithium manganese-oxide ($LiMn_2O_4$, Li_2MnO_3, or LMO), and lithium nickel manganese cobalt-oxide ($LiNiMnCoO_2$ or NMC) as their cathode material. LIBs being energy dense and long life reduces the frequent surgical replacement of batteries. LIBs have no memory effect and low self-discharge rate is currently better than other batteries but safety issues like damages to the battery physically or during charging is to be considered as its electrolyte is toxic to the cell as being used in the implantable applications [[53], [54], [55] Lithium base batteries finds its applications to power implantable devices such as pacemakers, neurostimulators, cochlear implants, implantable cardiac defibrillators, cardiac resynchronization

The batteries system that are being discussed in this section based on material are lithium base batteries, alkali and alkaline earth metal batteries and other batteries. On the basis of application batteries are further divided in to primary source battery, rechargeable battery and biodegradable battery. The battery system that are characterized based on the structed are novel batteries and flexible batteries.

2.6 Batteries to power biomedical devices and Classification on the basis of material used in the manufacture of the battery.

2.6.1 Lithium-Based Batteries:

The first biomedical battery made was the lithium base battery. They are two types of battery one is primary source battery which is nonchargeable the other is secondary source which is a rechargeable power source. The prior is called lithium battery while the latter is also called lithium ion battery. Lithium metal has the highest place in the electrochemical series, which indicates its highest theoretical voltage, and along with being smallest cation in size has the highest theoretical energy density. 2061 $mAhm^{3}$ and 3861 $mAhg^{-1}$ are the theoretical energy density for lithium electrode.[56], [57] The characteristics requirement for the biomedical device battery to have a reliable and predictable discharge profile is accomplish by the lithium base batteries[58], [59].

There are different types of lithium batteries being manufactured today and they are categories and named by the electrode material they are made from. Two electrodes are used in lithium batteries one is anode which is made of lithium while different set of electrodes are available to be used depending on the characteristic’s requirement like lithium iodine (Li/I2), manganese oxide (Li/MnO2), carbon mono fluoride (Li/CFx), silver vanadium oxide (Li/SVO) or hybrid cathodes (Li/CFx-SVO). Lithium ion battery being an energy dense battery are more used in medical devices especially in rechargeable applications because of comport to user but the safety factor of lithium batteries is always taken into consideration as being used in implantable device being safe is the compulsory. While lithium-ion battery uses lithium cobalt-oxide ($LiCoO2$), lithium iron-phosphate ($LiFePO4$), lithium manganese-oxide ($LiMn2O4$, $Li2MnO3$, or LMO), and lithium nickel manganese cobalt-oxide ($LiNiMnCoO2$ or NMC) as their cathode material. LIBs being energy dense and long life reduces the frequent surgical replacement of batteries. LIBs have no memory effect and low self-discharge rate is currently better than other batteries but safety issues like damages to the battery physically or during charging is to be considered as its electrolyte is toxic to the cell as being used in the implantable applications [[53], [54], [55]

Lithium base batteries finds its applications to power implantable devices such as pacemakers, neurostimulators, cochlear implants, implantable cardiac defibrillators, cardiac resynchronization.

devices, drug delivery systems, and bone growth generators. Most devices of today technology utilize lithium base batteries for single application and lithium ion for rechargeable application despite having different alternative batteries being available.[53], [60]. The applications of the lithium battery will be further discussed in this paper.

2.6.2 Alkali Metal and Alkaline Earth Metal Batteries:

Lithium is a first alkali metal but being toxic to the human body researcher had found interest in the direction of biocompatible and biodegradable batteries. Sodium and potassium are alkali metals while calcium and magnesium are alkaline earth metals that are found in human body. These metals are the part of the body and are nontoxic. The concept which draw the researcher in this direction is to create a biodegradable and more biocompatible battery as these metals are easily available and are cheap. This further lower the cost the raw materials for the manufactures for creating a cost-effective device. Battery is the source of power for the IMDs but not every IMDs require a single source of power or their requirement cannot be fulfilled either because of the volume constraints or shape constraints. The electronic IMDs technology has advanced enough and they are creating batteries of different shape and sizes because of the different material characteristics requirement. When the requirement is that battery must be thin than the physical damage can easily lead to electrolyte leakage which can be dangerous because of the toxic electrolyte and battery as a whole so biocompatibility and biodegradability is required for such applications.[15], [61]

The alkali metal battery made from sodium is sodium ion battery (SIBs) which is made from $Na_{0.44}MnO_2$ cathode, a nano-sized $NaTi_2(PO_4)_3$@C anode and electrolytes containing Na^+. This battery found its applications in wearable and implantable devices as it being biocompatible and flexible and have high volumetric energy and power density[62] Similarly development and research is going on with potassium ion, calcium ion and magnesium ion battery. Many different batteries of sodium-sulfer and potassium-sulfer have been made but they are not considered safe for IMDs applications.

2.6.3 Other Batteries:

Lithium batteries are the primary source of powering IMDs for about the half of the century, during this period many new batteries have been developed some of them will be discussed in this section. (). Silver-oxide (AgO) battery has found its applications in ingestible electronics battery. This battery is considered safe in is operations as it is thermally stable and does not cause thermal runaway[63]. Cathode is made from silver oxide while anode is made from zinc. Silver-oxide battery is used in endoscopic capsule and the its energy density is close to LIBs[63], [64].

2.6.4 Non-Rechargeable Battery:

The single use power source is primary and non-rechargeable battery. This type of battery has been in use for many decades and can easily be able to find its application in numerous

IMDs including, pacemaker, neurotransmitter. They have enough power storage capacity to power IMDs like pacemaker for numerous years.[61]. The characteristics of these batteries are; high energy density, low self-discharge, thermal and chemical stability, and long enough battery life to support the IMDs during its operation. Lithium-carbon monofluoride (Li-CF_x), lithium-iodine (Li-l_2), lithium manganese dioxide (Li-MnO_2) and lithium-silver vanadium oxide (Li-SVO) have been in use for IMDs [61], [65], [66], [67], [68], [69].

2.6.5 Lead Acid Battery:

Lead acid battery is a conventional battery that has been in the market for the availability of storage of electrical energy since 1859 and this is the first rechargeable battery for the purpose of commercial use. It has been more than two centuries but it is still in use today because of it advantages. Theses batteries are cost effective and reliable on the basis of per watt. Very few batteries can match their cost effectiveness and found their applications in uninterruptable power supply, mini golf cars and automobile and power backup systems.

The constructions of the lead acid battery are that they are composed of lead alloy as the pure lead is soft and cannot support itself in the structure of the battery therefore others metals are mixed with it like calcium, tin selenium and antimony are added to enhance its mechanical strength and electrical properties. The added tin and antimony change the properties of the battery make the cycle deeper and helps in deep charging which was not possible on the pure lead batteries. The problem of the self-discharge is handle by the added calcium metal in the mix but as a result the positive electrode swells as a result of overcharging there for battery management system is required and recommend for its applications.

Lead acid battery typically provides or have the capacity of 200-300 charge-discharge cycles for the applications of deep cycle. The depth of discharge also changes the life cycles of the battery. The life cycle of lead acid battery is quite short as compare to the life cycle of metal batteries like lithium ion battery or sodium ion battery this is mainly because of grids effect or grid corrosion that happens on the positive electrode and cause the deprecation of the active metal or the material on the battery terminal. The life cycle or the aging of the battery also depends on the different conditions like the discharge current and the temperature of the batteries; higher the discharge current and higher the temperature more aging effect of the battery is and less life cycle will it have.

Lead acid battery are easy to use and does not require many components but the limit of charging must be considered. Lower voltage charging will cause the built-up of sulfidation on the negative terminal but the high voltage will cause the ageing effect more progressive. Therefore, it must be used in moderation limit. Sulfidation can be reserved but ageing or corrosion is permanent.

One of the problems of the moderation of lead acid battery is that they are slow to charging and require 12- 20 hours of charging to be fully charged to maintain it cycle life. There is also a problem that this battery must be remained in its fully charges state when not in use as otherwise will result in the built-up of sulfation of the electrode and reduces its performance. Adding carbon can help in reducing the sulfication but it will result in the decrease in the energy density of the battery.

Figure 2.6.5: Lead acid Battery working is shown in the figure[70].

CHAPTER 3: EXAMPLE OF MEDICAL DEVICE

3.1 Pacemaker:

Cardiovascular and heart disease are the leading cause of death globally. It is an estimate made by World Health Organization that about 17.9 million people deaths are caused by cardiovascular diseases in 2019 and 85 percent of these deaths are caused by hearth attack and stock[71]. 19.05 million deaths are estimated in 2020 and from the year of 2010 the death by cardiovascular disease has been increased about 18.71%[72] Therefore, to prevent unnecessary deaths early diagnosis and treatment is crucial for patient survival.[51].

In recent decades, the morbidity and mortality have reduced for cardiovascular diseases due to cardiovascular implantable devices (CIEDs) such as pacemaker, implanted cardioverter defibrillator (ICDs), or cardiac monitoring devices, as they provide accurate and continuous diagnostic and therapeutic options[73]. Continuous improvement is required in the field of CIEDs to reduce the device size and extend the life and durability of the battery.[51]

The first ever pacemaker implanted in 1958 by Ake Senning had a secondary battery installed of nickel-cadmium having 1.25V cell voltage and 190 mAH cell capacity. Nickel-cadmium being a rechargeable battery have low capacity and consequently have short life span. Early pulse generator is powered by mercury-zinc battery, cell which were combined in series to produce 4-8 volts battery. Mercury-zinc battery produce hydrogen gas as battery discharges which results in fluid leakage from battery if vent is not provided, which the hermitically sealed devices could not provide, because of this major disadvantage this type of battery are no longer in use. For some period, nuclear batteries were also used. They have an extended life span of about 30 years but they have high toxicity level and large device size and thus no longer in use.

Lithium-iodine battery were introduced in 1975, having high energy density and shelf-life have considerably extended the life of pacemaker along with the reduction in size. Lithium-Iodine battery have a capacity loss of about 10% for 5 years.[74], [75] The characteristic requirement for CIEDs are voltage (minimum, maximum), discharge current (initial, average, maximum), duration of current pulses (continuous, intermitted operation), size, high specific energy and power, long shelf-life and the ability to maintain its operation normally for different temperature and pressure conditions, the battery of the CIEDs must follows the safety protocols of all the implantable devices like biocompatibility, corrosion resistant, hermetically sealed, light weight, flat and small sized and reliable.

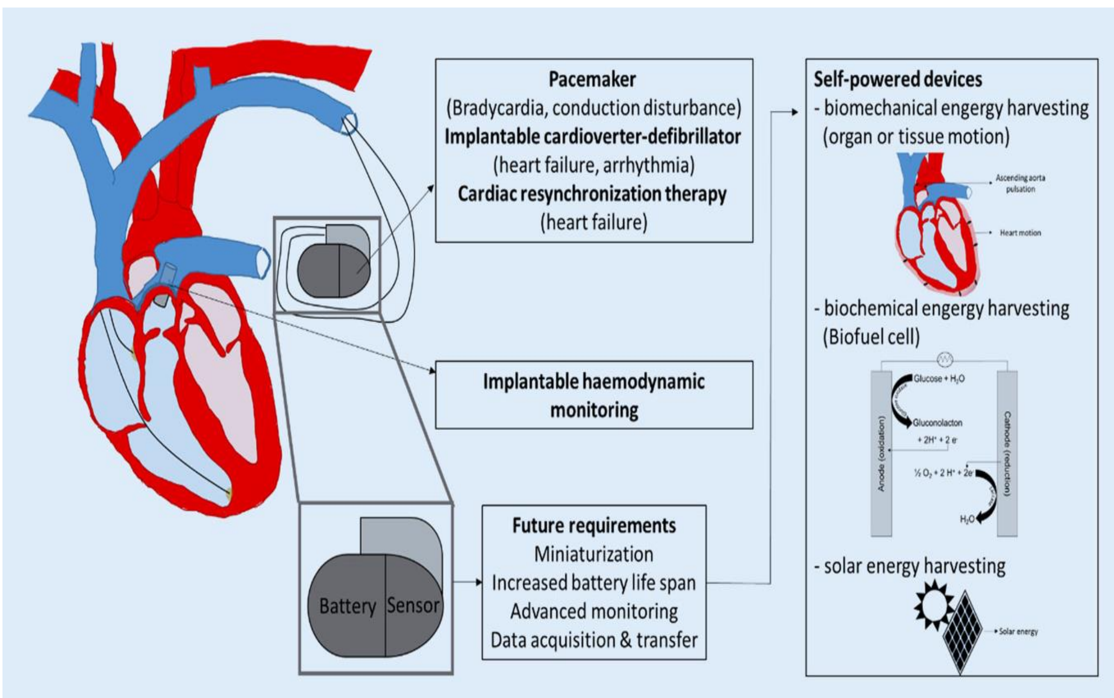

Figure 3.1: the figure shows the pace maker types, it part of battery and sensor and the future of packer make energy source.

Lithium solid cathode primary (non-rechargeable) batteries are used to power CIEDs and other advanced implantable medical devices due to the characteristic's requirements like, longevity, low self-discharge, high energy density and small size. Lithium liquid cathode system are not favorable for implanted devices because they have high self-discharge and toxicity even though they provide high discharge current.

Difference between different lithium base batteries are based on the electrode composition, electrodes which are being used in implanted medical devices are, Manganese dioxide (MnO_2), Copper oxide (CuO), Vanadium oxide (V_2O_5), and Carbon monofluoride $(CF)_n$. The impedance changes from 50–100Ωto 20,000–30,000Ω during the discharge life of the battery, current easily flow when battery is fully charged from negative anode to positive cathode, lithium from anode reacts with iodine in the cathode to form lithium iodine till its impedance gets higher as it discharges and it gets high enough that it hinders the flow of current and current is not able to flow easily.

3.2 Electric Wheelchair:

Electric wheelchair used many different types of batterires for its operations and the choice of the battery depends on many different constraints like the regulation of the country in which it is manufactured or to be manufactured for, for example FDA regulates the size of the battery in terms of capacity and types to be used for the applications of assistive medical technology. Electric wheelchairs are design so that that covers at least 20 kilometers for one charge travel. So, keeping the capacity in check many options of battery are there. Like lithium ion battery, lead acid battery and other metal battery like sodium metal battery. The best choice depends on the applications. Like lithium ion battery is the first choice but it is quite expensive so depend on the cost of the battery required all types of the batteries are in use. The lithium ion battery discuses in the previous chapters are all in use for the electric wheelchair applications.

CHAPTER 4: EXPERIMENT SETUP:

A standard lithium-ion cell is used for the experiment. The cell is placed in an acrylic box and this cell is immersed in silicone oil. Silicon oil is a dielectric oil and does not short circuit the cell. The oil is circulated in the from one side of the acrylic box to the other by travelling through the radiator fan assembly with the help of 12-volt Dc pump. For the experiment 12-volt dc pump, 5mm silicone tube, 130mm fac and radiator of dimensions 100x115x30 mm is used. Oil is pumped from one side of the box and it is cooled and pump out to the other side of the box to keep the temperature of the oil constant.

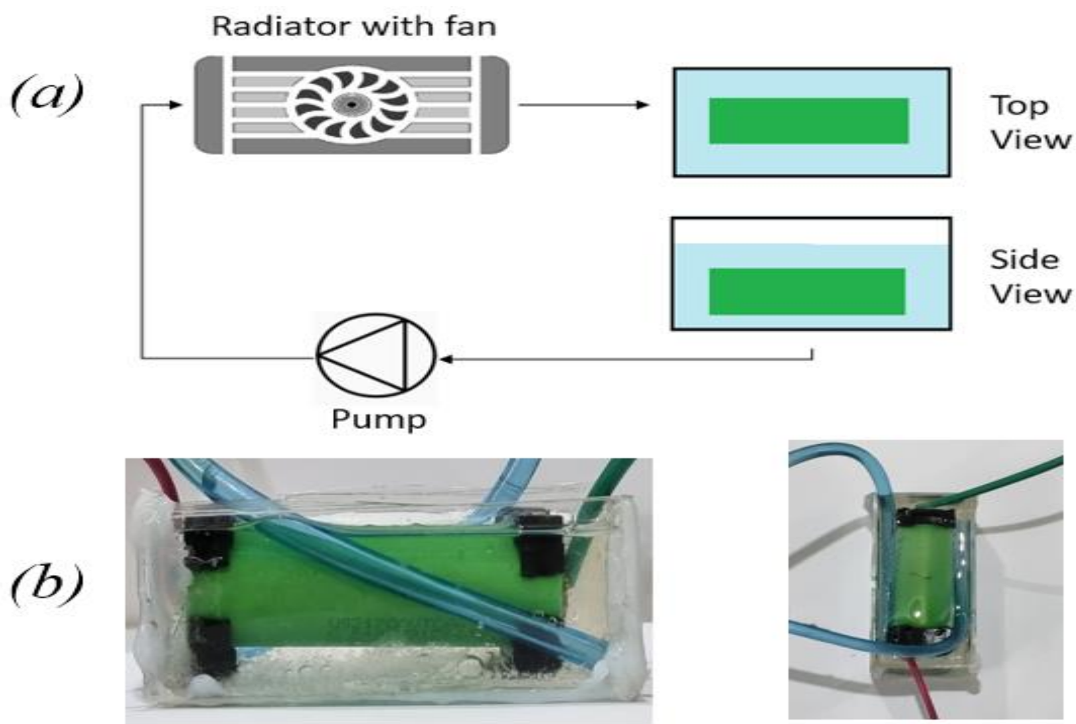

Figure 4.1 (a) Schematics of the Experimental setup, (b) Photographic image of the test setup of fully immersed cell.

The LIB used in the experiment is an 4000mah and 4.2V cell. The conditions for the charging of the cell are set at higher cutoff 4.2 volts and 100mmah current. The conditions for the discharge are set at lower voltage cutoff at 2.5. The cell is charged-discharged at 1C and 1.8C and during this process the temperature is measured with the help of thermocouple. Thermocouple is attached with the adhesive material to the cell and the temperature profile it noted with the respect to the time of progress of the experiment. Before the start of the experiment equipment are thoroughly checked and the 30 min resting time is selected between each charge and discharge of the cell. This time is arbitrary taken to thoroughly optimize the conditions of the cell.

Figure 4.2: thermocouple, Dc fan and Radiator is shown in the figure has been used for the experiment.

This is a natural cooling process and the purposes of this experiment is to compare with the liquid cooling process to check the effectiveness of the process. The experiment is carried out at 1C and 1.8C charging and discharging conditions. The battery is charges at at two different phase first phase is the constant current phase and the second is the constant voltage phase, it is charged till the charging current value becomes as low as 100mmah. While discharging is only a constant current phase. 1C means 4AH and 1.8C means 7.2AH for the 4.2V cell.

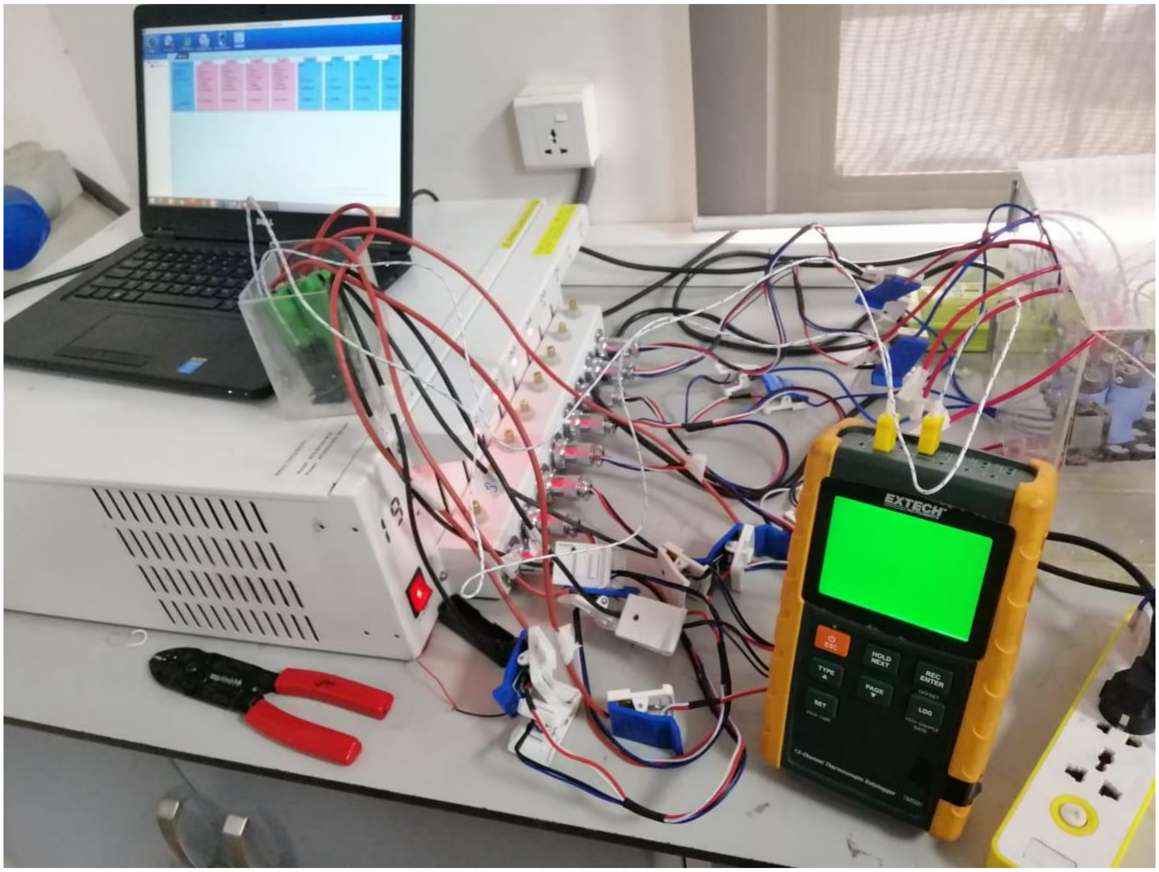

Figure 4.3: Battery investigator System is used for the experiment is shown.

For the experiment silicone oil is used as a coolant and figure 3.3 shows the temporal evaluation of skin temperature of the LIB cell. The maximum temperature rise in the process of 1C is 3.7 ^{0}C and in the process of 1.8C is 4.7^{0}C. The maximum temperature rises during the discharging process of 1C and 1.8C are 3.9^{0}C and 6.1^{0}C.

The charging and discharging process is the same as in the ambient conditions but the result is different, it is because liquid have higher thermal coefficient. The constant current phase in the 1.8 charge is different from ambient condition as it remain for a small time which in result in larger duration of charging time and lower increase in temperature. Maximum rise in temperature is show in the table 4.1.

CHAPTER 5: RESULTS AND DISCUSSION:

The results are discussed in this chapter in detail.

5.1 Natural Cooling:

This is a natural cooling process and the purposes of this experiment is to compare with the liquid cooling process to check the effectiveness of the process. The experiment is carried out at 1C and 1.8C charging and discharging conditions. The battery is charges at at two different phase first phase is the constant current phase and the second is the constant voltage phase, it is charged till the charging current value becomes as low as 100mmah. While discharging is only a constant current phase. 1C means 4AH and 1.8C means 7.2AH for the 4.2V cell.

Figure 4.1(a) shows the 1C charging and discharging temperature profile. The blue line is the temperature variations with respect to the time. Red line shows current profile and grey line is the line of voltage od the battery. The current line divides the charging temperature profile into two phase one is the constant current and the send is the constant voltage, this can be easily be seen in the figure 3.1. Temperature rises rapidly in the first phase which is the constant current phase. In this phase the heat is generated because of high value of current and in the second phase as the value of the current falls short the heat generated also falls shows and the temperature of the cell decrease. It must be noted that the graph shows a rise and falls of temperature as time and charging progress because of different heat is produced at different time. In the charging three different heat transfer are taking place; first one is the endothermic process of charging which decreases the temperature of the cell, the second is the heat is generated because of the flow of current and the finally heat transfer with the environment. The maximum rise in temperature is noted from the start of the experiment is noted to be 5.1 ^{0}C.

The discharging is shown at figure3.1(b) at 1C ambient conditions. The discharging is an exothermic process and in this process the current remains constant throughout the process. The reasons of different shape of the graph from the charging because in the discharging the exothermic process are more dominated and the heat is continuously produced. The discharging continuous till the voltage of the battery reaches at 2.5V. the maximum rise in the temperature is noted to be about 18.3 ^{0}C.

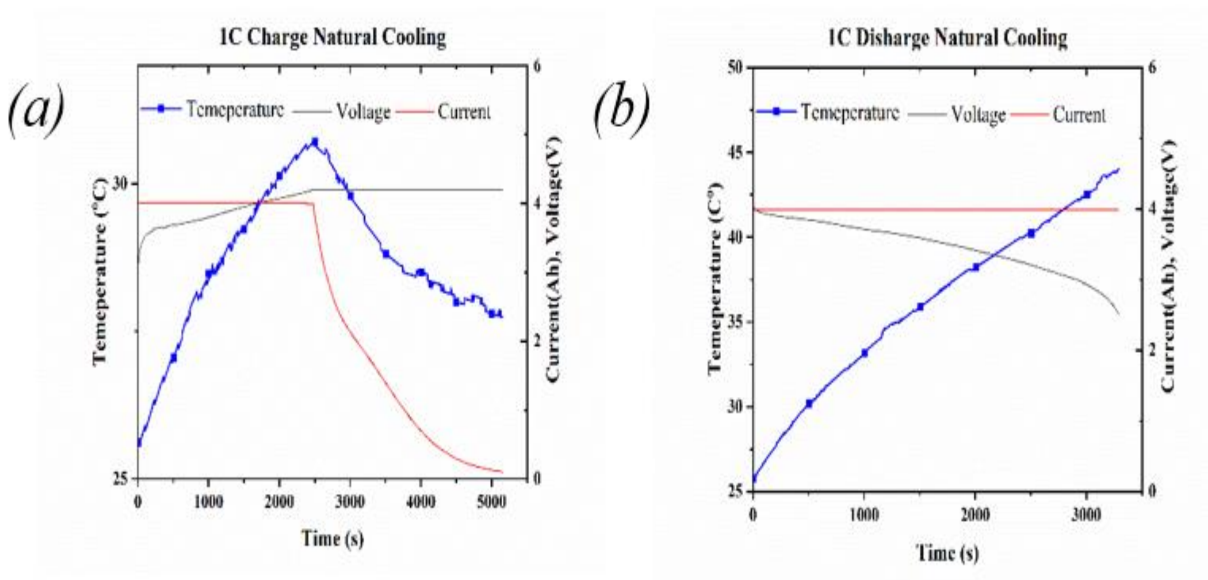

Figure 5.1 (a) Shows 1C charging skin temperature at ambient conditions, (b) Shows 1C discharging skin temperature at ambient conditions.

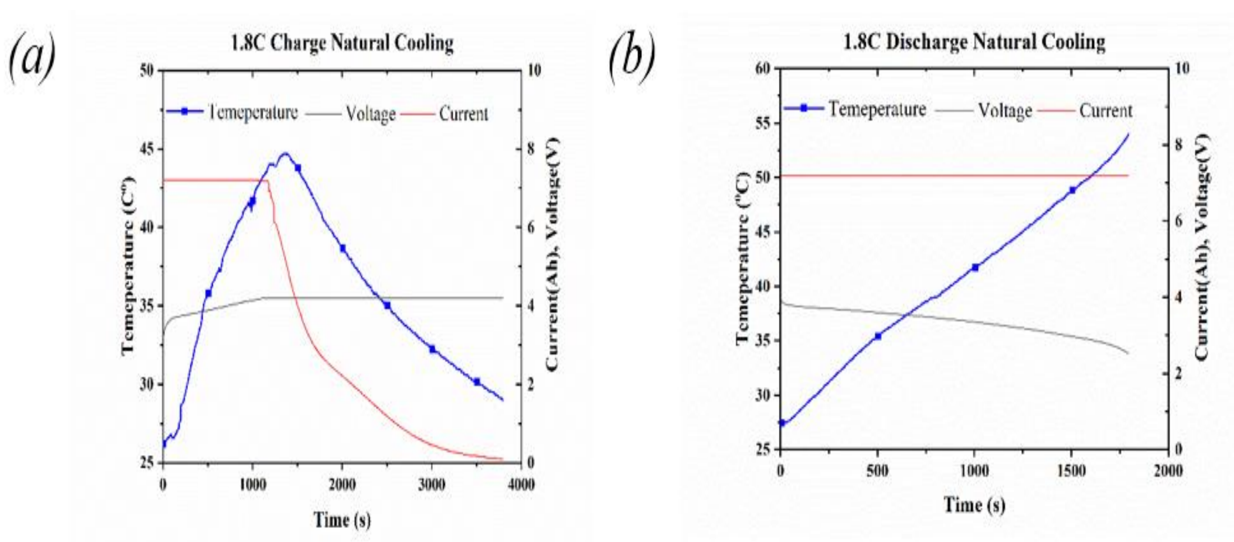

Figure 5.2 (a) Shows 1.8C charging skin temperature at ambient conditions, (b) Shows 1.8C discharging skin temperature at ambient conditions.

Figure 4.2 shows the charge and discharge profile at 1.8C. the same trend is followed in the higher C-rate but the rate of heat generated is also higher and therefore higher temperate rise is observed. 18.5^{0}C and 36.5^{0}C is the observed maximum rise in the temperature from the minimum starting temperature.

5.2 Liquid Cooling:

For the experiment silicone oil is used as a coolant and figure 3.3 shows the temporal evaluation of skin temperature of the LIB cell. The maximum temperature rise in the process of 1C is 3.7 ^{0}C and in the process of 1.8C is 4.7^{0}C. The maximum temperature rises during the discharging process of 1C and 1.8C are 3.9^{0}C and 6.1^{0}C.

The charging and discharging process is the same as in the ambient conditions but the result is different, it is because liquid have higher thermal coefficient. The constant current phase in the 1.8 charge is different from ambient condition as it remain for a small time which in result in larger duration of charging time and lower increase in temperature. Maximum rise in temperature is show in the table 4.1.

Process	**Natural Cooling**	**Liquid Cooling**
1C Charging	5.1 ^{0}C	3.7^{0}C
1 Discharging	18.3 ^{0}C	3.9^{0}C
1.8C Charging	18.5^{0}C	4.7^{0}C
1.8C Discharging	36.5^{0}C	6.1^{0}C

Table 5.1 Maximum rise in temperature for 1C ,1.8C charge and discharge for natural and liquid cooling.

Comparing the result of natural and liquid cooling give a better and clear picture of cooling effect of the two methods. Liquid cooling is more effective in cooling and controlling the temperature of the cell of LIB as compare to the natural process cooling. The vast difference is clearly shown in the table 4.1.

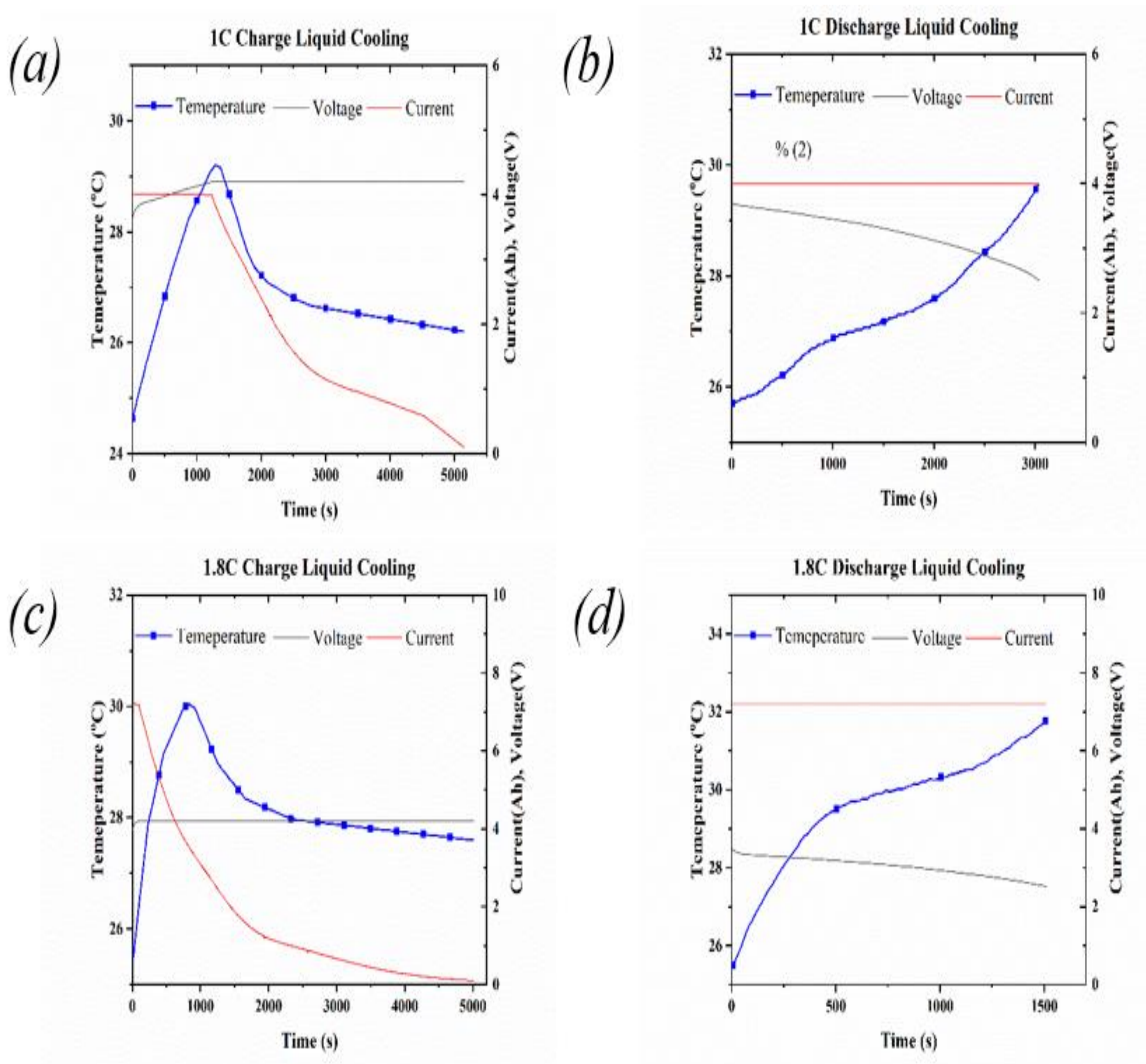

Figure 5.3 (a) Shows skin temperature at 1C Charging for liquid cooling, (b) Shows skin temperature at 1C Discharging for liquid cooling, (c) Shows skin temperature at 1.8C Charging for liquid cooling, (d) Shows skin temperature at 1.8C Discharging for liquid cooling

5.3 State of Charge:

It is the percentage of current capacity of the battery that is charged at any given time. It is usually expressed in-between 0 to 100%. The state of the charge for the given experiment is shown in the figure.

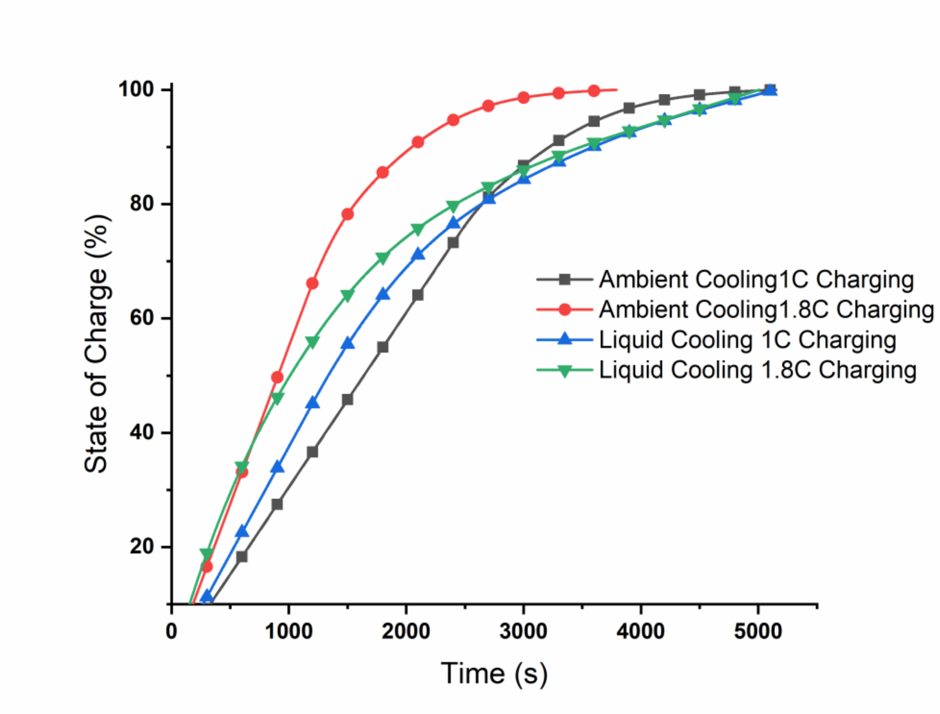

Figure 5.4 Shows the state of charge of cell during the process of 1C and 1.8C charge-discharge for natural and liquid cooling.

The graph shown above is drawn between the state of charge and time for 1C charging and 1.8C charging for natural convective cooling and for 1C and 1.8C charging of liquid cooling. The label of each graphical line is shown in the graph and the marker is set at every 100 points of the reading. The black line with square marker shows natural ambient cooling at 1C charging. The red line with circle markers indicates the reading and graphical line of 1.8C Charging at natural ambient cooling. The blue line with upside triangle shows 1C charging for liquid cooling and the green line with downside marker of triangle shows the liquid cooling at 1.8 C.

CHAPTER 6: CONCLUSION

The correct choice of battery is very important for the application of medical device. The safety, long life and cost all depends on it. The science and technology advancement are moving the battery technology to a compact, dense energy source which works at the body temperature or the temperature of the organ it is attached to which may require different types of thermal management. Liquid cooling thermal management is very important for high density batteries which have long hour use and utilization for better performance, safety and long-life and for different medical device batteries which mainly require higher power output. This paper has tested the thermal management of the LIB by liquid cooling and compare to the natural cooling. The results are shows in the table and graph form has indicated that the effect of keeping the peek temperatures in the operating range so that the LIBs are not affected in any adverse way. The direct contact silicone cooling has much higher cooling effect than natural cooling this make the operation of the utilization of the battery safe and make the battery runs in the optimal running temperature which in turn makes the life of LIB longer. The results are vastly dependent on the environment conditions and a slight change in the condition can vary the temperature profile of the experiment data graph. Environment is of paramount importance for this experiment too extreme of the temperature of the environment will make this setup inadequate as the power requirement of the setup is not intensive and largely dependent on the temperature of the environment. The advantage it holds against all other setup is that it does not cost much, easy to install, quite stable and effective, does not need a maintenance and finally is not energy intensive.

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