ENE 302 – Energy Conversion Processes II

WEEK 11: LITHIUM ION BATTERIES

INTRODUCTION

Energy demand and supply has always been one of the crucial factors for the evolution of civilization. Energy in the form of electricity is produced from solar, wind, nuclear power, burning fossil fuels, etc; however, production of electricity from renewable sources like, solar and wind need a storage device for their effective usage during depletion time. In this context, electrochemical energy storage devices such as batteries play an important role in the efficient use of renewable energy. Battery is a collective arrangement of electrical cells that stores and produces electricity by chemical reaction; storage and release is realised by electrons and ions. The first battery, Voltaic pile was developed by Volta in the year 1800. It consists of a series of copper and zinc discs separated by card boards moistened with salt solution. With more than 200 years of development, battery technology has achieved an era that batteries are safely used for transport of electricity without heat loss. They can be made in all varieties of sizes and shapes and useful for various applications.

Batteries are mainly of two types, primary and secondary batteries. Primary batteries are assembled in charged condition and the electrochemical reaction is mostly irreversible. For example; Lechlanche, alkaline MnO_2, silver oxide, and zinc/air batteries. Electrochemical reaction associated with secondary batteries is reversible. Hence the battery can be charged/discharged for a number of cycles and are named as rechargeable batteries. For example; lead-acid, nickel-cadmium, nickel-metal hydride and lithium ion batteries. According to the chemical reaction involved, rechargeable batteries can further be classified as lead-acid, nickel-metal hydride, zinc-air, sodium-sulphur, nickel-cadmium, lithium ion, Li-air batteries etc. Among the various rechargeable batteries aforementioned, Rechargeable Li-ion batteries have gained considerable interest in recent years in terms of highest specific energy, cell voltage, good capacity retention and negligibly small self discharge.

Li-ion batteries are the powerhouse for the digital electronic revolution in this modern mobile society, exclusively used in mobile phones and laptop computers. The success of commercial Li-ion batteries in the 1990s was not an overnight achievement, but a result of intensive research and contribution by many great scientists and engineers. Then much efforts have been put to further improve the performance of Li-ion batteries, achieved certain significant progress.

To meet the increasing demand for energy storage, particularly from increasingly popular electric vehicles, intensified research is required to develop next generation Li-ion batteries with dramatically improved performances, including improved specific energy and volumetric energy density, cyclability, charging rate, stability, cost and safety. There are still notable challenges in the development of next-generation Li-ion batteries. New battery concepts have to be further developed to go beyond Li-ion batteries in the future.

The basic structure of a battery consists of five major components as shown in Figure 1. There are electrodes (anode and cathode), a separator that prevents electron flow between the electrodes, a current collector on the outside of each electrode, and a case or enclosure. Electrons enter and leave the current collectors via current collector tabs, which connect the battery to the external circuit that contains the load to be powered or the source for battery charging. In a typical battery, set of chemical reactions occur during its operation. One of the Lithium-ion batteries types is Lithium Iron Phosphate ($LiFePO_4$). In this battery, generally the anode material is a form of carbon while the cathode material is $LiFePO_4$ material. During charge or discharge, the reactions occurring in the two electrodes for discharging can be written as in equation (1) and for charging as in equation (2):

$$\mathbf{LiFePO_4 - xLi+ - xe - xFePO_4 + (1\text{-}x)\ LiFePO_4} \qquad \mathbf{(1)}$$

$$\mathbf{FePO_4 + xLi+ + xe - xLiFePO_4 + (1\text{-}x)\ FePO_4} \qquad \mathbf{(2)}$$

During the Lithium-ion battery discharge, Lithium ions (Li+) are released from the anode and travel through electrolyte toward the cathode. When the Lithium ions (Li+) reach the cathode, they are quickly incorporated into the cathode material.

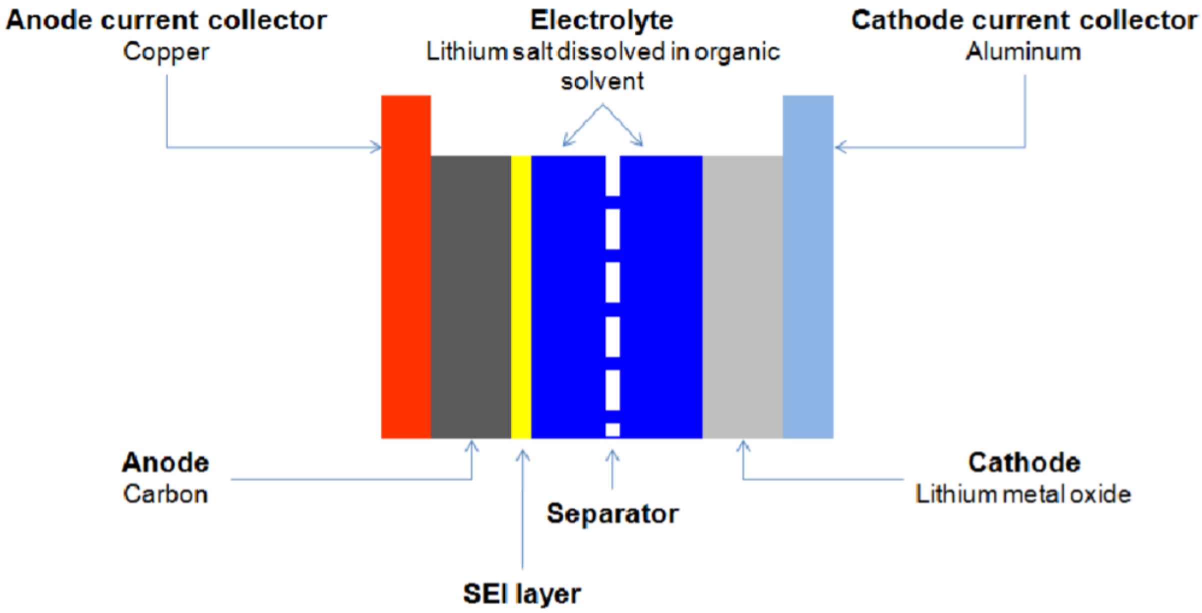

Figure 1. Basic Structure of a Battery

THEORY

Batteries are energy storage devices that are particularly useful for powering small portable devices like phones, laptops, and other electronic devices. However, batteries used in these applications all need to satisfy different requirements. Therefore, every battery structure should be engineered to meet the unique design constraints imposed by these different applications. These constraints include number of cells or cell voltage, battery capacity, energy density, cost and size. Therefore, it is important to have knowledge about these main factors to be able to choose the best battery for our desired application usage. Next section would provide a brief information on the mathematical calculations of these factors.

Let's start off with how the lithium-ion battery works. Batteries store and releases energy by moving electrons from one "end" of the battery to the other. Then we can use the energy from those moving electrons to do work for us, like power a drill. These two battery "ends" are known as electrodes. One is called the anode and the other is called the cathode. Generally, the anode is made from carbon and the cathode from a chemical compound known as a metal oxide (cobalt oxide, for example). The final battery ingredient is known as the electrolyte, and it sits in between the two electrodes.

In the case of lithium-ion batteries, the electrolyte is a salt solution that contains lithium ions hence the name.

When you place the battery in a device, the positively charged lithium ions are attracted to and move towards the cathode. Once it is bombarded with these ions, the cathode becomes more positively charged than the anode, and this attracts negatively charged electrons. As the electrons start moving toward the cathode, we force them to go through our device and use the energy of the electrons “flowing” toward the cathode to generate power. You can think of this kind of like a water wheel, except instead of water flowing, electrons are flowing.

Lithium-ion batteries are great because they are rechargeable. When the battery is connected to a charger, the lithium ions move in the opposite direction as before. As they move from the cathode to the anode, the battery is restored for another use.

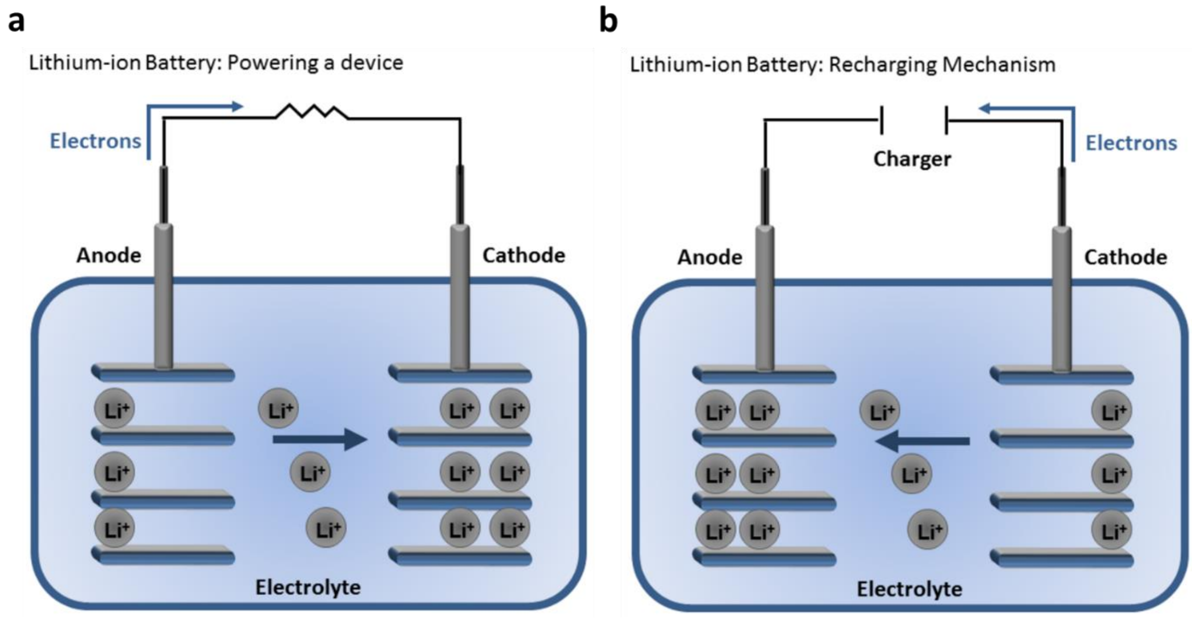

Figure 2. The process of (a) discharge and (b) recharge of a Li-ion battery

MATHEMATICAL MODEL

1. *Number of cells or cell voltage*

Different type of batteries have different cell voltages. For example, lead acid battery has a nominal voltage of 2 V while this value is in the order of 3.6 for lithium cells. Considering the fact that portable electronic devices are designed to operate at typical values of 24, 36, or 48 V, a number of cells should be connected in series to acquire the desired net voltage. A nominal 36 V pack could be made from 10 lithium cell or 18 lead acid cells.

2. *Battery capacity*

Battery capacity is published by the manufacturer as a nominal rating for a given set of discharge conditions. The battery capacity can be defined by looking at three different parameters: 1) battery voltage, 2) rate of discharge (or C rate), and 3) amp-hour capacity. As already explained the voltage is defined with the type of battery. The C rate refers to the amount of current that a battery can sustain for one hour while remaining within a specified voltage range. For a typical 12 volt battery, this voltage range will be between 12 V to 10.5 V where 10.5 V is considered as fully discharged. Moreover, battery capacity can be judged by looking at its ampere-hour (or milliampere- hour) parameter. This rating implies the discharge rate in amperes that the battery can be expected to sustain for a period of one hour. The mathematical relation is:

Battery Capacity (Q) = Current (I) * time (t) (3)

A pack that can deliver 1 amp for 1 hour has a capacity of 1 Ah.

Another figure of merit that matters most when comparing the energy available in different battery packs is not ampere-hour capacity but the total energy stored in watt-hours. This parameter is defined by following equation:

Watt-hours = Battery Voltage * Ampere-hours (4)

According to this equation, a higher voltage battery pack with a lower capacity (Ah) can deliver the same total energy as a lower voltage pack with a higher capacity.

3. *Energy density*

Another parameter is energy density of a battery. This parameter refers to the energy in watt-hours per unit mass of a battery:

$$\textbf{Energy Density = Watt-hours / mass} \qquad \textbf{(5)}$$

References:

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