THERMAL MANAGEMENT SYSTEMS FOR EV'S AND HEV'S

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ABSTRACT

Seeing how electric vehicles are the future of automobiles in general, it has become crucial to manage heat properly, so as to maximize the efficiency and range of the vehicle. Most complex systems use Li-Ion batteries as there are several advantages to this, such as maximize range, minimize weight and space used by batteries. The high power density of Li-Ions batteries allows it to be a perfect candidate for electric vehicles given the current state of technology. One of the conditions that comes with such a battery pack is its optimum operating temperature which lies between 15 and 30 degrees Celsius. The battery must have a thermal management system, either passive or active, wherein it always stays within this range. This paper aims to answer the major questions which deal with how to most effectively manage heat in an EV or HEV by comparing multiple solutions.

Keywords: battery cooling, BTMS, HVAC.

1. INTRODUCTION

A battery has many varying characteristics based on many factors. Characteristics such as specific energy, specific tension, operating conditions, auto discharge rate, charge time, toxicity and C-rate (which is the charge/discharge rate). The definition of C-rate is the capacity in terms of Ah. The capacity is rated 1C when a fully charged battery can provide 1 amp for 1 hour. Life cycle, recycling and materials used are also of great concern for battery development. [1].

These characteristics vary on factors such as energy demand, load, operating temperature, ambient temperature and many more things. The variations occurring are different for different battery chemistries. Majority of the battery systems deployed in vehicles are: lead batteries, alkaline batteries, lithium batteries and sodium batteries.

The main focus of this paper will be understanding and thermally managing Lithium Batteries. The paper will begin with understanding what the batteries are exactly and then proceed to the various solutions to deal with thermal management.

2. UNDERSTANDING LI-ION BATTERIES

Li-Ion batteries are known for having high specific energy, high standby times (low auto-discharge), no memory effect and low maintenance requirements [2].

Memory effects of batteries are generally observed in Nickel-based batteries. It is when the battery appears to "remember" it's lowered capacity after being charged from a state of being partially discharged.

Though the battery poses problems such as overheating, explosion risks due to leakage and formation of crystalline structures between the electrodes. The biggest disadvantage is the cost per kilo-watt of energy and the requirement of a good thermal management system for maximum efficiency [3].

2.1 Kinds of li-ion batteries

Based on the kind of material used in the cathode, various kinds of batteries exist. The three kinds of main cathodes are as follows [1].

a) Cathodes based on metal dioxides.
b) Batteries based on cathode spinel (Ex: Manganese oxide)
c) Cathodes with transition metal phosphates

The negative electrodes commonly tend to act as the "lithium sink" whereas the positive electrodes in the form of LiA_zB_y, acts as the "source of Li". The first two kinds of cathodes are the ones that tend to be most commonly used [4].

3. THERMAL BEHAVIOUR OF LI-ION BATTERIES

There is an ideal temperature for Li-Ion batteries to function ideally. The reason this happens is that the battery can't get too hot or too cold. If this happens, then the battery doesn't perform as designed, and as a result, this could be detrimental to the overall performance and operation of the vehicle.

If the battery is too cold then the battery capacity and autonomy is reduced, as well as its ability to operate. If the battery gets too hot then it destabilises, it's safety, power and life cycles are impacted. An example of the effect of temperature is shown in Figure-1.

The graph in Figure-2 indicates the effects of temperature on the capacity of the battery. The capacity is an indicator of how much charge a battery can retain.

As seen from both the graphs both extremely high or low temperatures are conducive for the battery performance. Hence an ideal temperature range is often prescribed by the manufacturer. Thermal management systems need to deal with this and dynamically adjust the operating conditions based on performance requirements.

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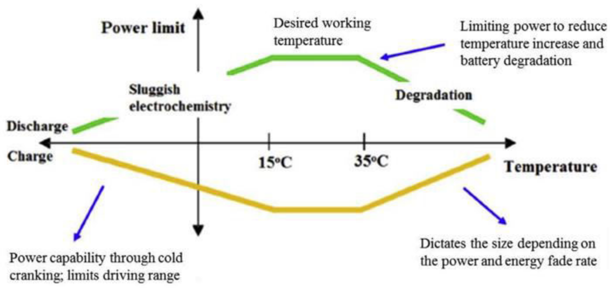

Figure-1. Effect of temperature on charging and discharging of a typical Li-Ion battery system. [5]

It is therefore understood that temperature can have detrimental effects on the battery. It affects the charge acceptance, round trip efficiency, electrochemical system, reliability and so on. In fact, higher temperature can also cause a film to deposit in the solid electrolyte interface [8]. Other adverse impacts include anode and electrolyte decomposition, unwanted chemical reactions between cathode and the adhesive or the cathode and the electrolyte [9].

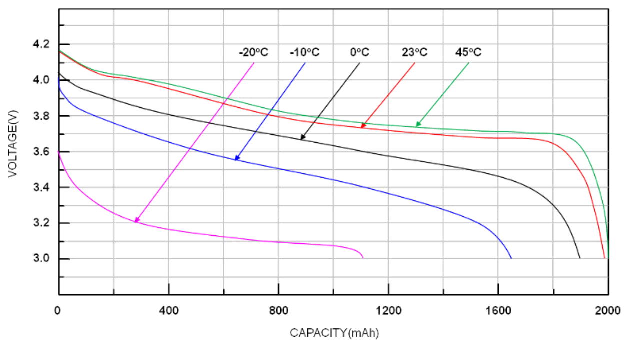

Figure-2. Effect of temperature on the capacity of a typical Li-Ion battery system. [6]

3.1 Thermal behaviour of Li-Ion batteries

A lot of things can happen inside the battery, to the electrodes, which may lead to the reduction of the overall system capacity. The increase in impedance or diminution of active materials, for instance, may lead to a loss in power. In a Li-Ion battery there are several factors that vary the thermal characteristics of the battery.

The heat in the battery comes from three primary sources namely ohmic loss, transport of Li^+ ions and the activation (interfacial kinetics) [10].

The main point of heat generation is the positive electrode. In fact the heat generated here is larger than all of the heat generated anywhere else in the entire battery. The heat generated is greatest during fast charge and discharge cycles. The heat generated is explained below.

3.1.1 Sources of thermal variation

The two main sources of heat in a Li-ion battery are released by the Joule Effect and the heat given out by electrochemical actions. The Joule Effect arises from the resistance to the charge transfer in the accumulator [7].

During operation, the discharge current and the charge current provide most of the heat. Here, the Joule effect is largely predominant.

The State of Charge (SOC), which is the remainder of energy inside the battery and the Depth of Discharge (DOD), which is the amount of energy depleted from the battery, which link closely to the chemical process of diffusion of Li^+ions, also dictate how much heat is generated.

The overall ambient temperature also plays a crucial role in dictating the heat generation. At higher temperatures the the electrochemical reactions are stimulated faster and internal resistance decreases. This in turn leads to a higher rate of heat generation.

Even the materials of cathode significantly impact the heat generation of the battery.

3.2 Mechanism of heat being generated in battery

It is important to have a clear idea of the structural composition of Li-Ion battery. Like many other batteries, it comprises of a positive, negative electrode and a separator. All these three components are porous in their composition [10].

Basically a Li-Ion battery could be understood as a concentration cell. During the process of discharge, Li^+ ions are "sourced" by the positive electrode and taken in by the negative electrode. The discharge process is the opposite.

The reactions for the process are given below [11]:

At positive electrode:

$$Li_xM_yX_z \rightleftharpoons Li_{x-k}M_yX_z + kLi^+ + ke^-$$

At negative electrode:

$$C_n + kLi^+ + ke^- \rightleftharpoons Li_kC_n$$

The overall cell reaction:

$$M_yX_z + C_n \rightleftharpoons Li_{x-k}M_yX_z + Li_kC_n$$

Where m is the metal atom and X is the anion group. [13]. It is important to understand these reactions to understand where exactly the heat is coming from. It comes from the exothermic reaction taking place by the processes mentioned above in the equation. The heat is generated maximum during charging and discharging process. Because reversible batteries can maintain thermodynamic relationship at a constant temperature and pressure, the heat given out is equal to the change in Gibbs free energy in battery reactions, as shown below. [13]

$$\Delta G = \Delta H - T\Delta S = -nFEe$$

Where ΔG is the Gibbs free energy, ΔH is the enthalpy change, T the absolute temperature and ΔS the

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entropy change. The faraday constant is given by F and E_e is the electromotive force of the battery.

4. THERMAL MANAGEMENT OF LI-ION BATTERIES

Having discussed the nature of Li-Ion batteries, we will now look in to how we can manage the heat generated by the batteries. There are two primary ways of thermally managing the batteries. Active Management and Passive Management.Passive systems are more cost effective, easier to maintain and require less energy, however it's generally difficult to have precise control over these systems. Active systems on the other hand are those systems wherein the cooling medium is actively pumped through the system. With an active system, it is generally easy to maintain the battery at the exact desired temperature, but it increases overall complexity and cost of the entire system. A schematic for an active cooling system can be seen in Figure-3.

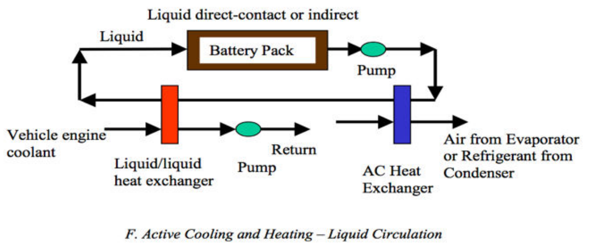

Figure-3. Active cooling system schematic.

4.1 Ideal characteristics of a battery thermal management system

The general Battery Thermal Management system of a car should ideally have some characteristics. These are explained below [13].

a) It should be able maintain cooling in hotter climates and harsher conditions.

b) The battery should be kept warm during the cold weather.

c) The temperature should ideally not vary by too much.

d) Should be low cost and have overall low maintenance, while being light weight at the same time.

5. SOLUTIONS FOR THERMAL MANAGEMENT

We are at an era where the demand from electric vehicles and therefore battery systems has reached a point where people expect it to work flawlessly. It has reached a time where people expect much more out the vehicle in terms of range and charging times. This means, the battery should now be able to retain its charge for a longer period of time and have extremely rapid charging times. The former demand correlates to how efficiently the battery manages its energy and the latter correlates to high charging rates, one of the limiting factors for which is thermal management.

For this the thermal management systems need to be innovative in the way they work. For our paper we will be focusing on the air cooled, liquid cooled and phase changing materials (PCM) to manage our battery systems.

5.1 Air cooled solutions

The air cooling options, right out of the bag, have some inherent advantages. Similar to the advantages in internal combustion applications, air cooling systems are cheap, simple and weigh less. Though the disadvantages are equally apparent. The air cooled solutions aren't very versatile, lack precise control and only operate for a pre-defined range of temperatures. Hence this solution clearly falls in the passive thermal management of batteries.

Air cooled systems come mostly in two variants, parallel and series. This can be seen in Figure-4 [13].

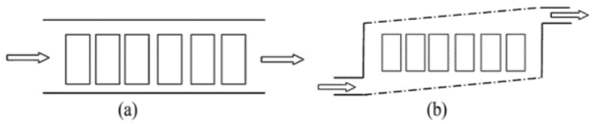

Figure-4. Air cooling shapes (a) series, (b) parallel.

When compared, the series cooled systems showed a temperature variation of 18 degrees Celsius, whereas the parallel cooled system showed a variation of 8 degrees [14].

However, it was noticed that these systems weren't very good at maintaining uniform temperature over the battery, especially in harsher conditions. For example, in one instance, it was seen that if the battery temperature rises up to 66 degrees, it would not be possible to bring it down below using passive air cooling alone [15].

Hence to tackle this, air conditioned air from the cabin itself was used to cool the batteries. This system is known as an HVAC system, or a Heated Ventilated Air Conditioning integrated system. One example of this is the current Toyota Prius, which uses the cooling system explained in Figure-5 (a). Another way to tackle the situation is to pre cool the air before it enters the battery pack, making the system and active cooling system. This is explained in Figure-5 (b) [13].

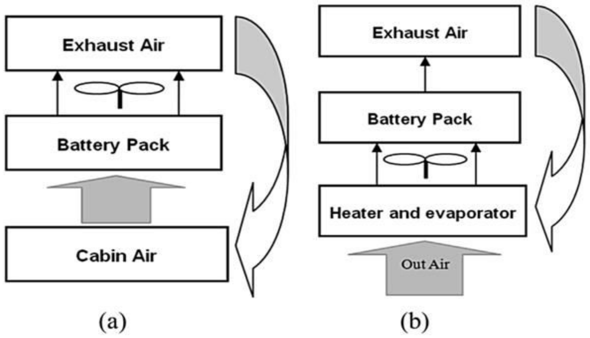

Figure-5. Schematic of thermal management using air (a) passive heating and cooling using cabin air (b) active heating and cooling using outside air.

5.2 Phase Changing Materials (PCM)

A phase changing material is any substance that has a high heat of fusion. Heat of fusion or enthalpy of fusion of a substance is the change in the substance's enthalpy which results from providing energy, generally heat, to a specific quantity of that substance causing a change in its state, occurring at a given constant pressure. A PCM is able to store large amounts of energy or heat when changing states from solid to liquid or vice versa. PCMs come in three main categories which include organic and inorganic PCMs and eutectics [1].

It was found that PCMs not only absorb large amounts of energy but also stabilise temperature during the process of phase changing [16].

However, there are still some problems in this area and further research needs to be conducted before actually deploying this technology to the mass market. The major problems with this technology are its passive nature, cost and its volume expansion.

5.3 Liquid cooling

Liquid cooling is an active thermal management system with some very clear advantages. Similar to internal combustion engines, liquid cooling provides precise control over the temperature but also comes with some inherent disadvantages, such as high complexity, weight, costs and requirement of external flow circuits and pumps. They also tap into the energy output of the battery, reducing efficiency.

The liquids generally used for cooling systems include water, glycol, oil and acetone. A battery pack liquid heat exchanger system can be seen in Figure-6.

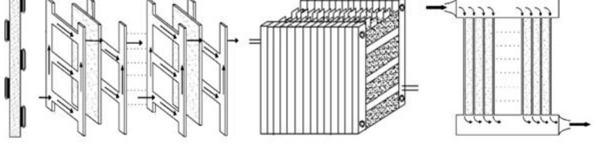

Figure-6. Battery pack liquid heat exchanger structure.

Cars such as Tesla, Chevrolet Volt use a liquid cooling system to meet the varying external environmental conditions they are sold in. Nissan Leaf uses an air cooled system, however it is found that the advantages of liquid cooled systems outweigh its disadvantages and liquid cooled systems generally fair better than air cooled ones.

6. FUTURE SCOPE AND CONCLUSION

Gone are the days of combustion engines where the heat wasted was very excessive. The future rests with these efficient battery technologies and soon, as most manufacturers shift to EV's and HEV's, the research and development for BTMS will rise exponentially. This paper briefly looks at the heat generation patterns and how to deal with them using current technology. This is a crucial part of any system and much more in-depth analysis is needed to understand how these systems interact with power electronics, varying loads, motors, etc. India has plans of selling only electric vehicles by the end of 2030. For this ambitious plan to come true, research like this will be highly valuable. The precise nature of thermal management to maximize the already low range of these vehicles makes these systems far more important and complex. Engineers will need to come up with better solutions soon to meet the rising demand for reliable electric vehicles.

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