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A Detailed Review on Cooling System in Electric Vehicles

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Abstract: *The temperature rise is the major factor that influences the functioning of Lithium-ion batteries (Li-Ion). To refine the heat efficiency of the battery there are various methods to dissipate the heat. Selecting a correct cooling technique for a Li-ion battery module of an electric vehicle (EVs) and deciding an ideal cooling control approach to maintain the temperature* between *5° C to 45° C is necessary. Maintaining an optimal temperature is essential as it increases safety, reduces maintenance cost, and increases the service life of the battery pack. When choosing a cooling technique various trade-offs are made among various parameters like weight, cooling effect, temperature consistency, and cost. In this paper four lithium-ion battery cooling methods: liquid cooling, phase changing material cooling , dielectric oil cooling, and thermoelectric cooling is discussed .The paper also consists of an elaborate study on Advantages, Disadvantages, and Applications of these four types of cooling systems*.

1. Introduction

Electric vehicles offer many advantages over a conventional IC engine automobile. These advantages are energy efficiency, no noise, does not depend on fossil fuel. Electric motors are more efficient than IC engines by converting more energy to drive the vehicle. Various other features bring EVs under lime-light like regenerative braking, EVs have smoother acceleration and braking systems, more cost-effective. However, there are many challenges faced that are related to the battery module. The battery emits a large amount of heat which needs to dissipate most effectively and keeping the battery cool. This helps in increasing not only the efficiency of the battery but also its health. High temperature (> 50°C) can increase the growth of the solid electrolyte interface and increase the internal resistance. This increase would reduce the power delivery significantly. Under extreme conditions, the separator will melt and cause a thermal runaway of the cell. Battery temperature plays a major role in the availability of the charging and discharging power, cell balancing, and charge acceptance during regenerative braking. Not taking an account of the rise in battery temperature can lead to a thermal runway which causes the battery to rupture, explode or cause a fire. This not only puts life under threat but also causes property damage. This paper discusses various methods which can be used to cool Li-Ion batteries.

2. Cooling system in electric vehicles:

The basic types of cooling system in electric vehicle are listed below:

1. *Lithium-Ion Battery Cooling*
2. *Liquid Cooling*
3. *Phase Changing Material Cooling*
4. *Air Cooling*
5. *Thermoelectric Cooling*

2.1. Lithium-ion battery

Lithium is a very light metal and falls under the alkaline group of the periodic table. It has three electrons and an electronic configuration of 1s2,2s1. Lithium has the highest tendency to lose an electron, and this property makes lithium highly unstable. Whereas lithium metal oxides are a more stable form of lithium. Individual lithium-ion cells can achieve a very high voltage due to the very high reactivity of the metal [1]. A lithium-ion battery contains several modules connected in series and each module comprises individual cells connected in series and parallel [2]. A lithium-ion battery comprises three major parts: 1. Lithium Metal oxide, 2. Electrolyte, 3. Graphite. Electrolyte separates the lithium metal oxide from graphite. Lithium-ion batteries work in two stages: Charging and Discharging. During the charging stage, it connects the cell to a power source. It connects lithium Metal Oxide to the positive terminal (anode) and it connects graphite to the negative terminal (cathode). Electron in the valence shell of lithium gets attracted to the positive terminal of the power source. Electrolyte acts as a guard and does not allow electrons to pass. Electrons pass through the external supply and reach the graphite layer, and in the meantime, lithium-ion (Li+) pass through the electrolyte and get trapped in the space between graphite. When all the lithium-ion gets trapped between the graphite solid sheet, the cell is fully charged [3].

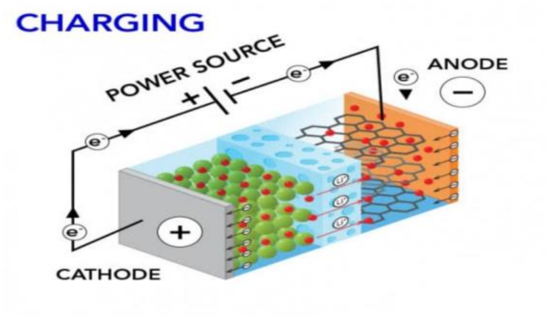

Fig-1: Charging Phase

Lithium-ion and Electron formed during the charging stage is a highly unstable stage so when the power source is replaced by a load the battery starts to discharge. The lithium-ion moves towards the metal oxide via the electrolyte to form a more stable lithium metal oxide state. The electrons start moving towards the anode through the load and thus we get electric current through the load. When all the electrons and lithium-ion go back to a more stable state it discharges the battery. Graphite used in the cell acts as a storage medium for the lithium-ion and does not actively take part in the chemical reaction. This process along with electricity also produces heat [4]. Lithium-ion batteries generate heat due to complex internal working mechanism like:1)exothermic chemical reaction 2)ohmic resistance 3)cell polarization due to difference in the battery potential during discharging and charging of open circuit[4]. Lithium-ion batteries undergo thermal runaway under certain conditions. Thermal runaway is the process in which at a critical temperature the materials inside these batteries start to breakdown exothermically and a lot of heat is generated. When the heat cannot escape as fast as it is generated this is a runaway reaction and it cannot be stopped. Here, if the proper cooling method is not used to dissipate the heat produced the cell explodes [5]. Cell explosion causes serious consequences. Thus choosing the correct cooling method for such a battery module is important. In this paper, we focus on different cooling methods used.

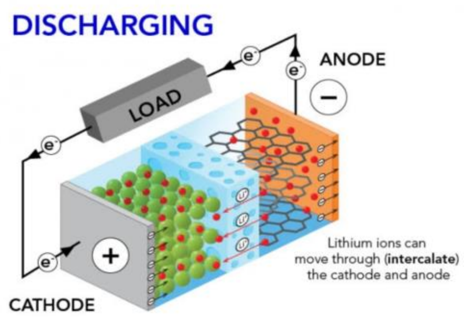

Fig -2: Discharging Phase

2.2. Liquid cooling

Liquid cooling has higher heat conductivity and heat capacity and so performs very effectively. It has its own advantage like ease of arrangement and compact structure. Liquid cooling helps in maintaining correct temperature of the battery pack [6]. According to researchers conducted, liquid cooling is almost one of the most promising cooling methods compared to any other. The microchannel liquid cold and warmth model of single-layer type liquid ion battery was established by Zhao. Tong devised a liquid cooling-based BTMS (battery thermal management system) for primary bipolar Lithium-Ion battery pack. Average temperature and temperature uniformity can be improved by increasing coolant flow rate or the plate thickness. The cooling performance of any fluid will depend on its thermal conductivity and its viscosity [7]. The main consideration for any cooling fluid is the specific heat. Plain water has the highest specific heat though it cannot be used alone so is therefore mixed with glycol. Glycol is the substance in the alcohol family. It is used with water to basically prevent it from freezing ad boiling. Glycol and water mix is inexpensive and is a very well-established cooling fluid. This mixture carries 50% of glycol, 45% of water and 5% of additives, which may include antifreeze, corrosion inhibitor, dye and antioxidant. Glycol has good specific heat capacity and also has good heat transfer properties [8]. Water-glycol systems are considered as indirect cooling. Pumping of glycol is done through the pipes which are surrounded by the battery. The supply of this water-glycol mixture is supplied using the supply pumps. BTMS using liquid cooling, the heat transfer is achieved by installing discrete tubing around the battery cells with a jacket around the battery cells which places the heated liquid or cooled plate to the battery cell surface or submerging the cells in a dielectric fluid [9].

Glycol used can be of two types:

1. Ethylene Glycol (EG):- This is used as antifreeze in the automotive engine cooling.
2. Propylene Glycol (PG):- PG has the same advantage as that of EG. In addition PG is considered non-toxic as well [10].

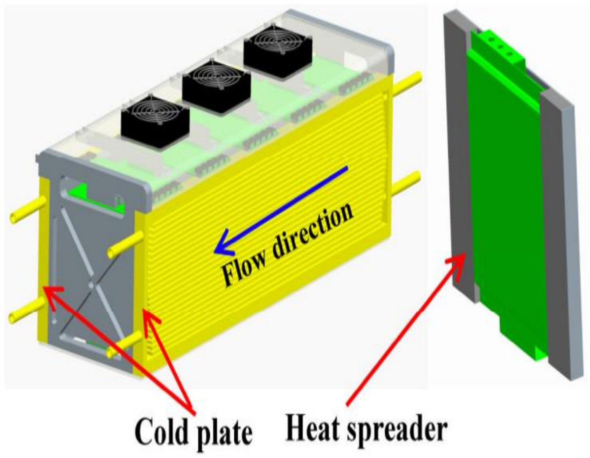

Fig -3: Conceptual design of indirect-contact liquid cooling system for battery pack of electric vehicle.

Battery cooling can be classified into two types1. Passive cooling 2. Active cooling based on the control strategies. In the passive cooling the coolant is cooled with the help of air through parallel flow heat exchanger whereas in active cooling the coolant is forcefully cooled with the help of the refrigerant through the internal heat exchanger. In passive cooling the heat sink for cooling is a radiator. In passive liquid cooling the heat transfer fluid is circulated by the pumps within a closed system. The circulating fluid will absorb the heat from the battery pack and it will release it via the radiator.

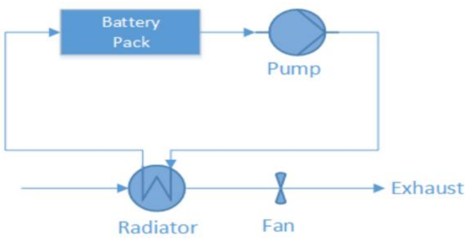

Fig- 4: Passive liquid cooling system

In active cooling there are two loops. The lower loop is called as the secondary loop and the upper loop is called as the primary loop. The primary loop is similar to the loop in a passive cooling system, in which the heat transfer fluid is circulated by pump. The secondary loop in active cooling is the air conditioning loop. In this the upper heat exchanger instead of being radiator works as an evaporator for cooling operation and connects both loops. When the heating operation takes place, the 4-way valve will be switched and the upper heat exchanger will start working as a condenser and the lower heat exchanger would work as an evaporator [11].

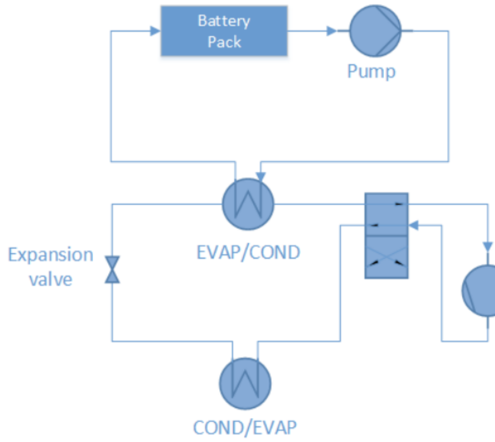

Fig -5: Active liquid cooling system

There are generally two types of liquid used in the thermal management of the systems. First is dielectric liquid which is also called as direct-contact liquid which can contact the battery cells directly, this includes mineral oils. Second is the conducting liquid which is also called as indirect-contact liquid which contacts the battery cells indirectly, this includes the mixture of ethylene glycol and water. Different layout is created depending on the type of liquids. In direct-contact liquid, normally the layout is submerged into the mineral oil whereas for indirect-contact possible layout can be a jacket around the battery module, discrete tubing around each module, placing the battery module on cooling/heating plate or combining the battery module with cooling/heating fins and plates. Indirect contact systems are generally preferred to achieve better isolation between the battery and the surroundings [12].

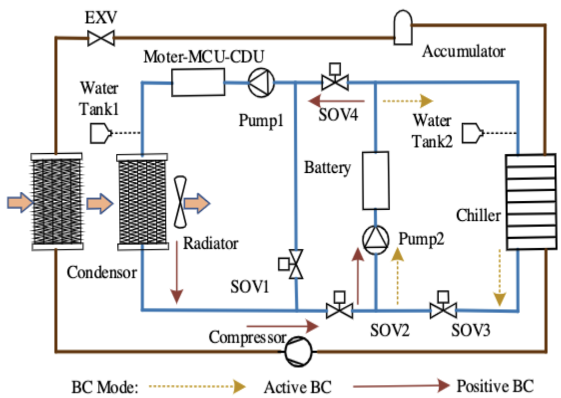

Fig -6: Schematic diagram of cooling system

Advantages: Water-glycol cooling needs less energy as compared to air cooling to maintain the same average temperature. It can resist corrosion and perform for longer intervals. Greater compactness and greater temperature uniformity among the cells. It has higher cooling rate compared to air-cooled system.

Disadvantages: Glycol loses potency over time. It is incompatible with the current additive chemistry. It also has potential electrical conductivity concerns, according to research by Afton Chemical. Any leakage by this technique could be a major problem for the car. Liquid cooling is complex than air cooling. This requires large space and the weight of vehicle. Cost of this is higher as compared to air cooling system [13].

2.3. Phase changing material

A phase-changing material is a material that releases or absorbs adequate energy at phase transformation to supply useful heating or cooling effect. PCM has such an application due to its property of having high latent heat. Commonly used PCM's are RT35, RT15 (Rubi Therma 15), EG5 (expanded graphite 5), and EG26. The working temperature of PCM ranges from -40C to 150C. PCM is the premier solution for a functional thermal management system of an electric vehicle by maintaining a constant temperature distribution even in any temperature condition [14]. Zhao et al epitomized different methods of thermal management systems, of which he concluded that PCM is a very effective technology for battery thermal management system [15]. Karimi et al experimented on a cylinder lithium-ion battery thermal management system using a composite PCM, which resulted in a decrease in the maximum temperature between the battery surface and composite PCM up to 70% [16]. Azizi and Sadrame Ali suggested a thermal management system for a LiFePO4 battery module with composite PCM and aluminum wire mesh. They found that the maximum temperature of the battery surface was reduced to 19%, 21%, and 26% at 1C, 2C, and 3C discharge rates respectively [17].

Classification: Phase Changing Materials are classified into three major categories: Organic (paraffin compounds, non-paraffin compounds), Inorganic (Salt hydrates metallics), and Eutectic mixtures [19]. The organic and salt hydrates phase-changing materials are favorable with applications with temperatures less than 100C (eg. Li-Ion Batteries) [18,20] . Eutectic mixtures can be used for temperatures up to 250C [20]. Organic materials have latent heat of fusion in the spectrum of 128 to 200KJ/Kg while Inorganic compounds have a range of 250-400KJ/Kg. Organics PCM is generally branched into two sub-categories: paraffin and non-paraffins. Paraffin is examined to be safe, chemically stable, dependable, and inexpensive [21]. Furthermore, they have low volumetric expansion through the phase transition and have low transition pressure. Paraffin is composed of chains of alkanes whose chemical structure and formula are $CH_3(CH_2)_mCH_3$ and C_nH_{2n+2}. Generally, paraffin phase-changing materials have their melting temperature and latent heat grow logarithmically with an increase in the number of carbon atom [21]. The main disadvantage of paraffin phase-changing material is a low thermal conductivity which is in the range of 0.15W/mK to 0.12W/mK [20,21]. Non-Paraffins can sub-categorized as esters, alcohols, glycols, and fatty acids [20,22]. Normally non-paraffins organic PCMs are distinguished by the high heat of fusion, non-flammability, low thermal conductivity, wild toxicity, and instability at high temperature. Moreover, fatty acids are the most important sub-category of inorganic PCMs. They have high heat of fusion compared to paraffin and no issue of thermal hysteresis and subcooling during freezing processes. The chemical structure and formula are $CH_3(CH_2)_mCOOH$ and $C_nH_{2n}O_2$ [21,23]. In fig.1 it can be noted that the latent heat and energy density of fatty acids increases with an increase in melting temperature and the normal range are 150KJ/Kg to 200KJ/Kg and 35kWh/m3 to 51kWh/m3 respectively [21,23,24]. The thermal conductivity of fatty acids is very low, i.e from 0.14K/mK to 0.17K/mK. Thermal diffusivities of fatty acids are in the range of 7.5m^2/s to 10-2m^2/s. Advantages of non-paraffin PCMs are good chemical stability, non-toxic, low volumetric expansion, compatibility with storing materials, high latent heat and energy density, no effect of sub-cooling and phase segregation. Disadvantages of non-paraffin PCMs they are more expensive when compared with paraffin and salt hydrates. The cost of non-paraffin PCM is approximately 2 to 2.5 times of paraffin and more than that when compared with salt hydrates 21,23].Inorganic PCMs are sub-categorized into two parts: salt hydrates and metallics [21]. Salt hydrates are a mixture of alloys of inorganic salts (AB) and water (nH2O), to form a compound with a corresponding chemical formula as AB.(nH2O). In this type of PCM, melting/solidification is a dehydration/hydration of the salt. This causes an issue of salt hydrates i.e. non-congruent or sedimentation processes during melting. This is caused due to dehydrated salts being heavier than water and tend to sediment at the bottom of the container. When hydration needs to be activated, the system is distinguished by areas of dissimilar salt concentrations, and therefore complete hydration is not possible. However, resolutions for this problem have been already found, for instance, mechanical stirring, encapsulating the PCM to avoid the separation of dehydrated salt from its water content, and also adding special thickening materials [21]. Dannemand et al, suggested the utilization of proper thickening agents, such as carboxymethylcellulose (-CH2-COOH) or Xanthan Rubber [19]. The other issue with salt hydrates is their super-cooling, because of the low nucleation property of the material. It means that the nucleation rate of salt hydrates is very low at transition temperature and the material needs to be super-cooled before nucleation is naturally activated in the salt hydrates. It means that it releases the thermal energy which is stored in the material at a much lower and thus decreasing the exergy efficiency of the heat storage system. There is little evidence that the addition of a nucleation agent or even injecting nuclei can activate the cooling process [21]. Altogether, the advantages of salt hydrates are high latent, high thermal conductivity, low volumetric expansion during melting, low level of toxicity and corrosivity(compatible with plastics), and cheap when used in pure form [20,21]. The last classification of inorganic PCMs is metallics. Metallics are low temperature melting metals [21,22]. They have high volumetric energy density but because of high density; they have low specific energy density. PCMs have high thermal conductivity, so it does not need thermal conductivity enhancement [21]. The other category is eutectic mixtures. Eutectic mixtures of 2 or more PCMs, which at the specific configuration, melt at singular temperature [20].

Working: Phase Changing Material is a matter that absorbs and releases thermal energy in course of melting and freezing. When a PCM freezes, it releases abundant energy in the form of latent heat at a relatively constant temperature. On the contrary, when such material melts it absorbs an enormous amount of heat from the environment. PCMs recharge as the surrounding temperature fluctuates, making them ideal for a variety of everyday application that requires temperature control. PCMs have been developed for covering a wide span of temperatures from -40C to more than 150C. They normally store 5 to 14 times more heat per unit volume than materials such as Water, Mansory, or Rock. Amid many heat storage alternatives, PCMs are attractive because they offer high-density energy storage and store heat within a narrow temperature range.

2.4. Air cooling

Air cooling generally uses the principle of convection for transferring heat away from the battery pack. As and when the air runs over the surface of the battery, it carries with it the emitted heat by the surface. This technique of cooling is easy but at the same time not very efficient. Convection is a process in which bulk movement of molecules within gases takes place. At initial stage heat transfer between object and gas takes place through conduction, but the bulk heat transfer takes place due to the motion of the gas. When the battery gets heated thermal expansion takes place [25]. The lower layer which is hotter becomes less dense. We know that colder part is denser. Due to buoyancy, the less dense, hotter part rises up and the colder dense replaces it. This process is repeated and hence the convection process is carried and the heat transfer s carried out. Convection is carried out by two types. 1. Natural Convection 2. Forced convection [26].

1. Natural convection: When the convection takes place due to the buoyant force because of the difference in densities caused by the difference in temperature is called as natural convection. Example of this may be natural air.
2. Forced convection: When there are external sources used for creating convection is called as forced convection. These sources maybe fans or pumps.

These similar types of process are also used in the cooling of electric vehicles where the vehicles maybe cooled with the help of natural air or with the help of fan.

Advantages: Air cooling system is less complicated and has low cost.

Disadvantages: Air cooling process cannot be used for most new high-performance applications due to the power density required and the wide range of ambient temperatures it needs to face. It is not possible to extract sufficient heat from the battery with the help of just the cooling system. Some cooling may take place within the battery because of the passing air but that is not sufficient to meet the full cooling that the battery needs. The fan for forced air extraction is big and it needs power from the battery to be driven which may result in large pressure drop [27].

2.5 Thermoelectric cooling

Thermoelectric coolers which are used in battery thermal management systems are a comparatively new technology in the field of electric vehicles. Their advantages are strong cooling capacities and reliable working potential and have increasingly gained attention for integration into battery thermal management system [28]. The main issue with the air and water cooling method is the cooling effect can be very limited under certain circumstances [29]. A thermoelectric module is a solid-state energy converter that consists of a bunch of thermocouples connected in series and thermally in parallel [30].

Working: A thermoelectric cooler (TEC) is based on the conversion of voltage to temperature difference. It refers to all of the transformation processes from heat to electricity and vice-versa. It operates according to the Peltier effect. The effect creates a temperature variance by carrying heat between two electrical junctions. A voltage is applied across joined conductor to create an electric current. When the current flows through the two conductors, heat is removed at one of the junction and cooling occurs. Heat is deposited at the opposite junction. The foremost relevance of the Peltier effect is to cool. The Peltier effect can also be used for heating or control of temperature [31].

Thermoelectric cooling has several advantages over other cooling methods like static device, no internal chemical reaction, noise-free, longer operation, no emission of hazardous gases, and minimum maintenance cost [32,34,35]. Disadvantages of TEC are low efficiency and additional power requirement which limits their commercial application [33].

Application: The thermoelectric cooler converts heat to electricity and vice-versa. TECs application revolves around two main aspects i.e. converting heat to electricity and electricity to heat [36]. There are numerous application of TEC. The main application of TECs is its use in cooling Li-Ion batteries, microprocessor of high configured computer and for building air conditioning system [37,38]. TECs have been also used recently in portable refrigerators, portable air conditioners and automobile cooling [39,40] . The most promising application of TECs is integrating it with PCMs for BTMSs to make a passive system into semi-passive system and thus increasing the efficiency of the BTMS [41,42,43].

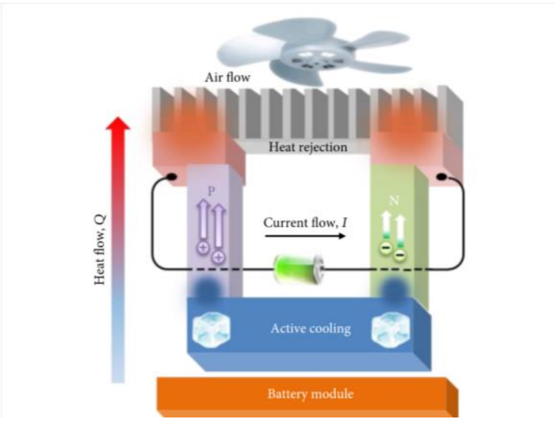

Fig -7: Thermoelectric cooling setup

3. Conclusion

The paper proposes on various battery cooling techniques of electric vehicles. The battery thermal management system (BTMS) is the most crucial element of an EV. During the charging/discharging mode of electric vehicles, a major focused area for the research is to maintain the optimal working temperature range of the batteries and reduce both the maximum temperature and temperature difference. Suitable and effective cooling methods will significantly reduce the adverse effect of high surface temperature of battery cells and efficiently augments the battery thermal efficiency. It also improves the safety of the vehicles and also increases the life of a vehicle. In all the above-mentioned battery cooling techniques, liquid cooling technique is one of the most reliable and promising cooling technologies. The techniques mentioned will significantly help improve the battery performance under high charging/discharging rate and attention should be given to compact design with cheaper cost.

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