Materials selection for hybrid and electric vehicle battery pack thermal management: A review

Shankar Durgam∗, Priyanka Datir, Onkar Tawase, Dipak Savant, Ganesh Tapkir, Ravi M. Warkhedkar, Nikita M. Gawai
Department of Mechanical Engineering, College of Engineering Pune - 411005, India
E-mail: *sod.mech@coe@in

Abstract. This paper reviews materials for hybrid and electric vehicles battery pack thermal management required for efficient working of batteries in any climate conditions. Lithium-ion (Li-ion) battery cells are being used for electric or hybrid vehicles because they having high density of energy and long life cycle. Battery lifetime and performance of Li-ion batteries depends on operating temperature. The higher operating temperature increases capacity and decreases life of Battery. Thermal management strategies which are based on air, water, phase change material (PCM) and heat pipe are discussed and compared. After comparison, an efficient system of temperature management for battery pack is discussed. Phenomena of creating heat and temperature issues of Li-ion batteries are discussed in this paper. Then different strategies are reviewed and classified based on thermal cycle options. Improving the existing temperature control system and testing new technologies to reduce thermal issues is necessary, and efforts should be made to prioritize the thermal management system to improve temperature uniformity throughout battery pack, life of battery, and increase protection to battery packs.

Keywords: Lithium-ion battery, thermal characteristic, thermal management system, control strategies, Heat generation, phase change material.

1. Introduction

In recent times, electric vehicles are becoming more attractive and popular due to their aspects like reduce the energy loss, reduce the pollution, environment friendly. There are different types of batteries such as lithium-ion (Li-ion), lead–acid, nickel metal hydride (Ni-MH) are used for electric vehicles applications because, their high specific power and specific energy density. Compared to other batteries, Li-ion batteries mostly used in electric vehicles as well as in hybrid electric vehicles, because they have high power, light weight, does not require to charged continuously. When a lithium-ion battery operates at low temperature the lithium dendrites build up in battery anode and result is State of health (SoH) of the battery decreases significantly. [1, 2, 3, 4, 5]. When the battery temperature exceeds the fixed point, the most powerful reaction occurs out of control [6]. In addition, when a battery reaches a thermal escape, 12% of total heat released by battery is sufficient cause hot explosion in nearby batteries [7]. This is especially dangerous when using lithium-ion batteries. battery thermal management system (BTMS) is a mandatory for lithium-ion battery systems, at high temperatures [8, 9, 10, 11, 12]. There are two main purpose of battery thermal management system (BTMS): 1) keeping batteries running under optimal conditions and improving electrical performance and life of
battery 2) preventing heat dissipation from occurring and improving safety. Most battery-powered heat transfer systems, like air conditioning, liquid cooling, and phase change (PCM). Therefore the main objective of this work is to explore the different materials for battery thermal management technologies available from the previous literature applicable for recent hybrid and electric vehicles.

2. Li-ion batteries for electric vehicles (EV) and Hybrid electric vehicle (HEV)

The most trusted battery for electric and hybrid vehicles, their general considerations, mechanism and configuration, market survey etc. are discussed in this section.

- **General Considerations:** The efficiency of electric vehicles (90%) is high compared to electric-powered vehicles (30%). And electric vehicles operate at high torque with low revolution speed. It has a fast torque feedback and converting kinetic energy into electricity from brake torque (Regenerative braking system to HEVs) is also attractive. The problem of heat loss in electric cars is less than that of an engine-driven car. Compared to liquefied petroleum or gasoline, the battery power of batteries is very low, which means that an electric car needs more battery cells to obtain the same performance given by an engine-powered car. Li-ion batteries widely used in electric vehicles because of their high energy content (140 Wh/kg and 500 Wh/L respectively) compared to nickel-metal hydride (NiMH) batteries (65Wh/kg and 150 Wh/L), owns the HEV market.

- **Mechanism and configuration:** Lithium-ion battery method is given in Fig. 1 During charging, Lithium+ ions moves from negative electrode (cathode) to positive electrode (anode) through separator diaphragm to form discharge cycle, and vice versa. The cathode is make from graphite. An anode is made of lithium containing a substance such as: coated oxide (viz., lithium cobalt oxide - LiCoO2), poly-anion (viz., lithium iron phosphate - LiFePO4) or spinel (eg Lithium manganese oxide - LiMn2O4). Lithium salt solution which is not an aqueous solution such as ethylene carbonate or diethyl carbonate is used as an electrolyte. Current collector of negative and positive electrode is made from copper (Cu) and aluminum (Al) respectively. The mechanism of a lithium-ion battery with the charging and discharging mechanism is shown in Fig. 1.

- **Market Survey:** Future growth of the EV could predicted by introducing a great deal of work done by Special niche manufactures. It shows that NiCd and NiMH are the two most sought after EV batteries in 2000. The inconsistent intention set by manufacturers says that undeveloped battery automation, like limited proof of public electric vehicle weight production could be observed. In current years, lithium-ion batteries are well-known among EV manufacturers for their durability, high power output, high range of development, and fast charging time.

![Figure 1. Lithium-ion battery mechanism (A123Systems. (2008))](image-url)
3. Temperature problems in Li-ion battery
   - The performance of this battery cells depending upon operating temperature and operating capacity. Li-Ion cells gives good result when it working within sufficient electrical, thermal energy. On the other hand, the cells will be damaged and will not be replaced.
   - Charging power increases due to over-voltage over stable power supply, leading to current flow, which creates problems.
   - With an anode, the current copper collector deteriorates. It causes an increasing battery discharging capacity also power of battery, however, ions of copper reduced as an irreversible copper. The condition is very dangerous and results in short circulation between the anode and the cathode.
   - Chemical reaction rates are related to line and temperature. As operating temperature decreases the reaction rate and the current carrying capacity during charge or discharge decreases. We says that, power of battery reduced.
   - Operating temperature exceeds the acceptable limit.
   - Battery life is reduced due to low temperature.

4. Operating temperature
   For increasing battery performance parameters, it is important to avoid thermal issues like heat losses, overheating by controlling temperature within limits. Battery power and battery cycle life are affected by the temperature, as shown in Fig. 2, and Fig. 3. At the same time, temperatures divides same to ensure battery life, lifespan. That is the reason why a battery temperature control is required for a battery system. When the temperature rises between $20 \degree C - 40 \degree C$, power of battery reaches its peak, as shown in Fig. 2

![Figure 2. Graph between power of and temperature [13]](image1)

![Figure 3. Graph between Battery Cycle life and temperature (Electropaedia, 2014)](image2)
Due to anode plating, Lifecycle of battery decreases slightly below 10 °C and decreases rapidly above 60 °C because of damage to material of electrode, as shows in Fig. 4. Temperature can control between 20 °C and 40 °C protects function, health of the cycle.

5. Battery thermal management strategies (BTMS)
The performance of automobile (EV and HEV) is mainly depends upon the battery thermal management. There are various strategies available for battery thermal management for obtaining better performance and life of battery. These strategies includes: air cooling and heating, liquid cooling and heating, cooling and heating of refrigerant, phase change materials (PCM) are mainly discussed here.

5.1. Air cooling and heating
This program uses the spirit as a community. The air comes from the atmosphere (static air cooling/heating) and the modified air comes behind the heater or evaporator air conditioner (active air cooling/heating). The system is limited to certain hundreds of watts/cooling power watts while in the operating system, power restricted to 1 kW, (Valeo, 2010). In both of cases power is limited their supply supplied because of blower. There is no need to add additional air intake, as the air system provides heating / cooling and ventilation function. But waste air not connected again to this cabin. In some application, air-conditioning is installed back of battery to return heat to exhaust air. This prevents the combination of exhaust air, also provide more energy saving at the same time.

5.2. Liquid cooling and heating
In this system the liquid is used which transfer heat. We have two types of beverages that can be used for hot management systems. One is dielectric liquid and the other is a liquid. Dielectric liquid interacts directly with battery cells for example mineral oil. The running liquid can only interact with battery cells indirectly, for example mixture of ethylene glycol and water.

![Diagram of battery thermal management strategies](image)
Radiator is used as a cooling heat sink in the manufacturing process. Fig. 6 shows that the water system is inactive. In the case of a closed pump it is used to move the fluid. Battery release heat, it absorbed by fluid, it emits heat through radiator. Cooling capacity depends upon temperature difference between atmospheric air and battery. To improve performance of cooling fans are placed behind radiator. Liquid cooling system does not work if the dry air is above the battery temperature.

There are two pitfalls in this figure. The top loop called main loop. Bottom called second loop. Main loop similar to loop in an empty water system, in which fluid is transmitted through a pump. The second loop is air loop. High temperature switch acts as evaporator used to cooling operation, which used to connecting two loops together. In heating operation, four-way valve can replaced, high-temperature machine acts as condenser and the low-temperature machine acts as an evaporator. The heat function of the loop is known as heat pump loop.

5.3. Cooling and heating of refrigerant
The direct refrigeration system has A/C loop which similar to an active liquid system but in the refrigerator the system uses it directly as a battery-powered heat transfer fluid. The formal arrangement of ooling and heating of refrigerant is shown in Fig. 7.
5.4. Phase change material (PCM)
Phase-change material (PCM) is a method of temperature management of battery packs. It has a high hidden temperature and has a desirable melting point due to its ability to store and produce high energy. Heat will transmitted from battery, It creates heat, then deliver to PCM. It eliminates need for effective cooling / heating during most of the work because it takes more time to increase in temperature when minimum temperature is low, during hot days. It keeps the battery below the proper temperature, decreases heat slope in battery, it resolves the difference between high heat retention efficiency, low thermal conductivity (0.26 W/m K), there are many ways to make composite PCMs that include:

(i) Installed metal matrix in PCM;
(ii) overheating of stress equipment
(iii) addition of thermal conductivity to paraffin and
(iv) Improving thermal energy storage systems with unfinished exhausted structures.

The working of PCM mechanism is shown in Fig. 8 for performance of battery cells. In melting condition, PCM absorbs heat and stored it as ambient temperature up to higher volume. Temperature maintained in melting point for specific duration also increase in temperature takes time. PCM is use as conductor, buffer in hot battery handling unit. Single-phase PCM used as combination of an air conditioning system or liquid cooling system for battery temperature Management.

5.5. Thermo-electric module
There are two ways to increase the cooling/heating capacity of a passive air system. Another is to use thermo-electric modules. Other use of heat pipe. Thermo-electric module is able to
convert electrical energy into temperature differences and vice versa. The scheme diagram is shown in Fig. 9. To increase heat transfer by forced convection two fans are included. By combining air system and thermo-electric unit, system has capacity to chill battery which less than that of temperature of air, but power restricted 100 W, less than 1 kW. (Valeo, 2010). It is simpler to switch between cooling and heating temperature by reversing the size of the electrodes.

Figure 9. Thermoelectric cooling/heating system [14].

5.6. Heat pipe (HP)
Heating pipe is another way to improve the performance of synthetic air unit. Schematic of heating pipe is shown in Fig. 10. Flat copper part of heat pipe is under incomplete vacuum. To make capillary structure using sintered copper powder. Water is used as the active liquid in the heating pipe. Water on evaporator side absorb heat and evaporate below 100 °C because of inside pressure is low. water inside condenser transfer heat to that area and returns to liquid state again. This process happens repetitively. Given Schematic indicates formation of cooling pipe which is inside cooling system. Battery is located at the bottom of the heating pipe on the evaporative side. The cooling wings used for heat absorbs which is located inside heat pipe on side of twist. According to experimental outcome (Tran, 2014), heat pipe reduces thermal resistance by 32% in natural convection compared to a system no use of heat pipe. Temperature losses reduce by using air velocity convection method are about 20%. Fig. 11 show the heat pipe cooling system.

Figure 10. Structure of the heat pipe [15].
6. Observations from different technologies

(i) Forced-Air Unit: Forced-air cooling unit has simple, highly reliable, efficient and easy-to-use structure, but has some problems such as poor heat management (in addition to active temperature), unusual uniformity of heat distribution and hot escape.

(ii) Liquid System: The ambient temperature affects the idle cooling system, because the temperature of the atmosphere depends upon radiator, radiator diffuse heat by temperature difference between liquid and surrounding temperature. Under normal condition it works good, but at high temperatures not sufficiently work. Active cooling systems work best with heat. It can control temperature of battery within operating range and maintain distribution of temperature between cell parallels due to the high cohesive cooling temperature. Because of the many interlocking and operating parts, whole model is complex and difficult to maintain. As a result there are potential for leaks. Direct refrigeration cooling systems work better than an active cooling system because they can use the refrigerator directly for cooling purpose without using the refrigerator to cool down first, then coolant is used for cools system. Limitations of cooling system in the refrigerator are complex configuration, heavy storage, potential leaks and more.

(iii) PCM System: PCM cooling systems are very capable of heat management. Under atmospheric temperatures between 44 °C - 52 °C, inside temperature of cell package remains below 56 °C due to high temperatures and subtle temperatures. A great feature of PCM is it best suited for cold working conditions or surrounding. As temperature of battery pack increases above melting point of PCM, the temperature is maintained as ambient temperature. When atmospheric temperature maintained below melting point of the PCM it will be released to the battery module. Forming a PCM without new elements is easy, has less weight and requires less space. But it is hot and driven by electricity and volume changes due to the PCM-graphite feature.

(iv) Thermo-electrics: Thermo-electrics with minimal structure and light weight, it turns heating element into effective cooling agent with converting coating. It has no moving parts so it reduces wear, is reliable, durable and requires minimal care. And it is easy to replace it if it fails. Moreover, the performance is quiet and non-vibrating. Fig. 12 shows a combined liquid cooling system.

Figure 11. Scheme of heat pipe cooling system [16].
7. Recommended cooling system

7.1. HP + PCM
Thermal battery management using a combination of heat pipe and PCM introduced. Temperature of battery of electric is kept below 49°C. When using a heat pipe only at temperatures of 22 W, lower the ground temperature from 45 °C to 37 °C, and at 50 W decrease from 79.2 °C to 50 °C. Compare the combination of heat pipe with phase switching by 20 W, lowering the maximum temperature from 45 °C to 35.2 °C and 80 °C to 48 °C -50 W. combination of heat pipe and beeswax PCM used as an effective application of battery cooling application.

7.2. PCM Model (CLS+PCM)
The integration of PCM material with CLS is another method that can be used for hot battery management. PCM layers situated in battery pack. Advantage of PCM is that it has good thermal response, and CLS compensates for moderate temperature of PCM, Fig. 13

The combined liquid system with PCM system

Figure 13. The combined liquid system with PCM system [17].

The critical analysis of battery thermal management strategies for Li-ion battery types are given in Table 1. The comparison between different batteries is given in Table 2.
Table 1. Battery thermal management strategies (BTMS) for Li-ion battery

| BTMS          | Battery type                        | Design Parameters | Experimental conditions                  | Observations | Author /References |
|---------------|-------------------------------------|-------------------|------------------------------------------|--------------|--------------------|
| Air Cooling   | Li-ion battery (72 prismatic cells) | capacity = 5.19 Ah | $T_i = 40\, ^\circ C$ Battery load - 4.81 W | $T_{max} = 58.2\, ^\circ C$ | Park and Jung [18] |
|               |                                    |                   |                                          |              |                    |
|               | Li-ion battery (24 pouch cell)      | capacity = 2.2 Ah | $T_i = 27\, ^\circ C$ SOC(%) = 95 - 5 | $T_{max} = 58.2\, ^\circ C$ | Hong et al. [19] |
|               |                                    |                   | Discharge rate = 5 C                    |              |                    |
|               | Li-ion battery (8 cylindrical cells)| capacity = 3.6 Ah | $T_i = 20\, ^\circ C$ SOC (%) = 70 -100 | $T_{max} = 29.6\, ^\circ C$ | Mahmud et al. [20] |
|               |                                    |                   | Discharge rate = 7 C                    |              |                    |
| Liquid cooling| Li-ion battery (3 cartridge heater) | Water(Oblique Channel plate) | Battery load = 220 W No. of channel = 01 | $T_{max} < 50\, ^\circ C$ | Jin et al. [21] |
|               |                                    |                   | Discharge rate = 5 C                    |              |                    |
|               | Li-ion battery (rectangular cell)   | capacity = 7 Ah Water(straight channel plate) | Discharge rate = 2.6 Ti = 25 C | $T_{max} = 58.4\, ^\circ C$ | Huo et al. [22] |
|               |                                    |                   |                                          |              |                    |
| PCM           | 12 Ah prismatic cells               | PCM: Paraffin cell spacing = 1.5 mm; $k_{pgs} = 800\, \text{W/m K}$ | $T_i = 25\, ^\circ C$ Discharge rate = 5 C | Expanded graphite mass fraction between 15 - 20% is recommended | Wu et al. [23] |
|               |                                    |                   |                                          |              |                    |
|               | 6 Ah LCO cell based on 4.4 Ah Hitachi battery | Paraffin + Graphene nanomembranes; Nanofillers' t = 10 nm | $T_i = 25\, ^\circ C$ Discharge rate = 0.2 C, 1 C and 3 C; initial SOC = 98 % | Graphite + Paraffin gives better performance than TMS designed using graphene nanoparticle | Mortazavi et al. [24] |
| Heat pipe     | 16 LFP 18 AH prismatic cells joined in series | flat micro heat pipe array t = 3mm; tilt angle = 5° Heat pipe: 200 x 60 mm Fin: 20x24x1mm | $T_i = 27.5\, ^\circ C$ Discharge rate = 1C | Intracellular gradient smaller than 5 ° is noted | Ye et al. [25] |
|               |                                    |                   |                                          |              |                    |
| PCM + HP      | Aluminum cylinders with heating rods | PCM: Paraffin/EG; EG wt fraction = 16% Sintered-copper HP, dia. = 6mm | $T_i = 20\pm0.5\, ^\circ C$ Discharge rate = 5 C | Because of PCM addition to the module, maximum temperature reduces by 33.6 % | Zhao et al. [26] |
|               |                                    |                   |                                          |              |                    |
| PCM + CLS     | 5*6 1.1 Ah cylindrical cells collected in parallel | paraffin EG matrix with embedded flat plate pipes; k =10000 W/m K; cell spacing: 34 mm (x-dir) and 25 mm (z-dir) coolant: ethanol alcohol | $T_i = 35\, ^\circ C$ Discharge rates of 1 C, 2 C, and 3 C, 5 cycles | Liquid cooling + PCM take longer time to reach the maxi-setting temp of 44 °C in comparison to PCM + air cooled pipes | Huang et al. [27] |

C = Coulomb’s; means a fully charged battery rated at 1Ah provides 1 Ampere for one hour.
### Table 2. Comparison between different types of battery

| Battery Type          | NiCad | NiMH | Lead Acid | Li-ion |
|-----------------------|-------|------|-----------|--------|
| Sp. Energy (Wh/kg)    | 40-55 | 65   | 20-35     | 140    |
| Energy Density (Wh/kg)| 70-90 | 150  | 54-95     | 250-620|
| Sp. Power (W/kg)      | 125   | 200  | 250       | 300-1500|
| Internal resistance (mΩ) | 100-200 6V pack | 200-300 6V pack | <100 12V pack | 150-250 7.2V pack |
| Cycle life            | 2000  | 2000 | 4500      | 3500   |
| Charging time         | 1h    | 2-4h | 8-16h     | 2-4h   |
| Self discharging rate | 20%   | 30%  | 5%        | 10%    |
| Cell Voltage (nominal)| 1.25V | 1.25V | 2V        | 3.6V   |
| Operating temperature | -40-60 °C | -20-60 °C | -20-60 °C | -20-60 °C |
| Maintenance           | 30-60 days | 60-90 days | 3-6 months | Not required |
| Typical battery (cost $/kWh) | 280 | 500-1000 | 269 | 300-800 |

### Advantages
- High sp. power
- Long life cycle
- Low self discharge
- Robust
- Fast charge
- High energy density
- Simple storage and transportation
- Good electro-mechanical characteristics
- Long life cycle

### Disadvantages
- Low cell voltage (about 1.2V)
- High cost
- Cadmium is environmentally harmful
- Low cell voltage
- High self discharge
- Cadmium is environmentally harmful
- Limited service life
- Poor temperature characteristics
- Corrosive in nature
- Expensive
- High energy density
- Protection required
- Transportation problem

### Application
- Replacement for flashlight battery
- HEV’s replacement for flashlight battery
- Car battery, forklift, golf cart, backup power
- Consumer electronics

Sp. - Specific; std. - standard; V - Volts; h - hour; $ - US Dollar
8. Conclusions

From the study of materials selection for hybrid and electric vehicle battery pack thermal management and comparison between different battery packing heat management techniques, it is concluded that combination of PCM and heat pipe is most effective method of thermal packing of battery packs. The main conclusions can be made as follows:

(i) Combination of heat pipe and PCM is more effective and efficient, it was used in both EVs and HEVs. By using PCM and heat pipe, a significant decrease in temperature noticeable as compared to no cooling strategy especially during high emission levels. Also, the heat pipe + PCM module has longer operating time to reach set temperature of 50 °C as compared to PCM module only.

(ii) The maximum temperature controlled below 50 °C as the forced air assembly is used to improve the heat transfer rate.

(iii) In the case of cycle conditions, heat pipe + PCM module is reached at stable phase with the same temperature profile after the first cycle, while the only PCM module without HP continues to increase.

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