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Study on the effect of tab cooling on the lithium-ion battery pack life cycle

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Abstract

Electric vehicles are the future of mobility. Electric vehicles have batteries to store energy and the most common type of batteries used in electric vehicle's battery packs are lithium-ion cells. These cells have very high energy density and dissipate heat during charging and discharging cycles. There is a need to have an efficient cooling system to dissipate this heat. Bigger-size batteries in four-wheelers use liquid cooling to ensure faster charging and longer battery life. Surface cooling and tab cooling are two popular types of liquid cooling systems for battery packs. Surface cooling is a preferred type of cooling system as it is less complex and cheaper, but it creates a temperature gradient inside the cell which is detrimental to cell life. This work proposes tab cooling as a solution to improve the life cycle of lithium-ion cells. Two sets of the battery pack, one with tab cooling and the other without a cooling system were tested under different conditions for multiple fast charging and discharging cycles until their initial capacity was reduced by 30%. The results show that with tab cooling the battery performed better and battery degradation was reduced.

Keywords: Lithium-ion; Battery pack; Thermal management; Tab cooling; Battery life

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1. Introduction

Electric vehicles are the future of the automotive industry. One of the major issues that hinder the acceptance of an electric vehicle is the battery. It is a very expensive part of the vehicle and requires replacement at least once during the lifetime of the car. Lithium-ion batteries are widely used in electric vehicles (EVs). There are six types of lithium-ion battery chemistries available in the market. These are lithium-ion cobalt oxide, lithium-ion manganese oxide, lithium iron phosphate, lithium nickel manganese cobalt oxide, lithium nickel cobalt aluminium oxide and lithium titanate batteries. Lithium iron phosphate batteries which have a long life and lesser self-discharging are much preferred for two-wheelers. Lithium nickel manganese cobalt oxides are popularly used in bigger EVs as they have higher specific energy.

Lithium titanate and lithium nickel cobalt aluminium oxide batteries are also used in automotive applications. Most of the automotive industries are currently working on batteries that have higher energy density and can be charged quickly.

Battery thermal management is an emerging area in battery electric vehicles (BEV) where research work is carried out to improve the performance of the battery by optimizing the design of the cooling system [1,2]. As stated, lithium-ion batteries re-

Nomenclature

$C_{p\,cv}$ – specific heat capacity of calorimeter vessel material, kJ/(kg K)
$C_{p\,eg}$ – specific heat capacity of ethylene glycol, kJ/(kg K)
I_b – battery charging or discharging current
I_{loss} – current consumed by loss (heating due to resistance)
m_{cv} – mass of the calorimeter vessel, kg
m_{eg} – mass of ethylene glycol in the calorimeter, kg
q – power generated by the battery, W
SoC – state of charge of the battery
SoC_{to} – state of charge of the battery at the beginning of the charging or discharging
t_d – duration of the test, s
t_o – initial time at the beginning of the charging or discharging
T_f – temperature of EG at the end of test, K
T_{fcv} – temperature of CV at the end of the test, K
T_i – initial temperature of EG, K
T_{icv} – initial temperature of CV, K
τ – time at the end of charging or discharging

Abbreviations and Acronyms

BEV – battery electric vehicles
CV – calorimeter vessel
DC − direct current
EG – ethylene glycol
EV – electric vehicle
HEV – hybrid electric vehicles
HVAC– heating, ventilation and air conditioning
OCV – open circuit voltage
SOC − state of charge

ject heat during the charging and discharging cycle because of electrochemical reactions, phase changes and Joule's heating. If this rejected heat is not removed effectively, the temperature of the battery rises. Lithium-ion cells work very efficiently within the temperature range of 15°C to 45°C. The battery starts to degrade and lose its capacity when it operates at a lower or higher temperature range than the range that is recommended.

Generally, BEV battery life depends on the effectiveness of the thermal management system along with battery pack design, cell arrangement and operating conditions. A single lithium-ion cell provides around 3.6 V with a 2 500 mAh to 3 000 mAh rating. Present-day BEV requires a minimum of 48 V to a maximum of 800 V with a minimum of 10 kWh capacity. BEV battery pack capacity is rated in terms of kWh which is a product of total output voltage and Ah rating. To achieve such a high capacity, hundreds of cells are connected in series and parallel and are made in the form of a stack. Because of space restrictions in the vehicle, cells in the stack should be arranged as compactly as possible. In the stack, thermal management becomes challenging as spacing between cells and fluid flow through the battery stack has to be optimized to keep the battery at the desired operating temperature.

Air-cooled systems are a more attractive cooling technique for hybrid electric vehicles (HEV) and EV battery packs [3−9]. In air-cooled systems, the air is used as a cooling medium to maintain a uniform temperature and to control the temperature variation across the battery pack. The cooling effect is easily achieved by simply directing the airflow through the battery pack module. Air-cooled systems are effective when the battery pack is small and the ambient temperature is less than 20°C. As heat rejection per cell is less than 5 W [3], smaller packs have fewer cells arranged in series and parallel, and it generates less heat. Cooling can be improved with the addition of a cooling fan, cooling fins or heat sinks and proper air ducts [4]. Such systems can effectively function till 35°C of the ambient temperature.

Air-cooled systems are less expensive as the battery pack design is simple and it has a few components. However, in extreme conditions, especially at high discharge rates and higher ambient temperatures air-cooled systems are not preferred. Sometimes cells in the battery pack are cooled indirectly with the help of aluminium plates sandwiched between pairs of pouch cells. These plates have extended surfaces (cooling fins) which are exposed to airflow from the air conditioner [5]. Some studies also reveal that due to the better thermal conductivity and thermal diffusivity of the cooling plates, heat transfer of the cooling plate governs the cell temperature distribution by spreading the cell's heat over the surface [6−7]. Cylindrical cells cannot be cooled in this way, mostly they are stacked in the form of a matrix or arrays for the want of space.

Zhao et al. [9] investigated numerically the heat transfer characteristics of a cylindrical lithium-ion battery pack with air as a cooling medium. In their work, a parametric investigation was carried out to study the effect of different ventilation types, fluid velocities, spacing between adjacent batteries, the temperature of ambient air and the diameter of the cell on heat transfer. Though it was optimized, their study showed the temperature difference between cells arranged in the array. In addition, for better heat transfer, the spacing between the batteries should be optimized. Wang et al [10,11] studied the thermal performance of battery packs with different cell array arrangements. Air-cooling method was investigated by installing fans at different locations of the battery pack to obtain uniform temperature throughout the pack. Based on the simulation study, the effect of factors like cell array arrangement, spacing between the cell and fan location on cooling was discussed. Their study concluded variation in the temperature of the pack. So as to achieve better cooling, a fan should be placed on the top of the battery pack module with the cubical arrangement of cells (5 × 5 structure) in the battery pack [10]. Fan et al. [12] examined the effects of spacing and rate of airflow on the effective cooling of the air-cooled battery pack. It was inferred that decreasing the gap space or increasing the air flow rate will lead to a decrease in temperature rise and temperature difference. It is clear from the review that achieving uniform cell temperature across the battery pack of an air-cooled battery pack system needs proper spacing between the cells, uniform airflow and lower pressure drop.

In modern HEV and EV, a liquid-cooled system is a preferred mode of cooling because of its ability to absorb more heat than the air-cooled system due to the liquid's better thermal conductivity and specific heat [12]. In a liquid cooling system, a mixture of water and ethylene glycol or a dielectric fluid is used as a cooling medium to maintain a uniform temperature of the battery system. Liquid cooling effectively meets modern vehicle drive demands. Though quieter during operation, it has a possibility of coolant leakage in joints, if not designed properly. Liquid cooling can be achieved in different ways such as through discrete tubing around each module, with a jacket around the module, submerging modules in a dielectric fluid for direct contact, or placing the modules on a liquid-cooled plate heat sink [13]. The heat transfer medium could be water, glycol, oil, acetone or even refrigerants.

Apart from leakage, liquid cooling systems increase the weight of the cooling system and hence it may impact the range of the vehicle. So, both the cooling requirements and weight reduction are important from the point of view of battery cooling design [14]. Zhao et al. [15] proposed a new kind of cooling method for the cylindrically shaped battery pack which is based on a mini-channel liquid-cooled cylinder. The dependence of channel quantity, rate of mass flow, the direction of flow and size of the inlet on heat dissipation was numerically investigated. Teng and Yeow [16] compared the designs of various direct and indirect liquid cooling systems, the paper describes the cooling system design along with all its calculations.

Janarthanam et al. [17] discussed the requirements of a cooling system in a vehicle and how a liquid cooling system is better than an air-cooling system. Their work presents a way to determine the requirements of battery cooling system design targets, pack configuration and cooling method determination. Their simulation results demonstrated clearly that direct liquid cooling has advantages over indirect liquid cooling from the battery thermal management point of view. Research also reveals that the heat transfer from the internal cell structure to positive and negative electrode terminals (tabs) is higher than that from the radial surface (circumferential surface of the cylindrical cell). The tab temperature is higher at least by 5°C compared to the cylindrical surface [18]. The study also reveals that the cathode registered a higher temperature than the anode. Researchers are exploring various ways by which the thermal management of lithium-ion batteries can be improved without complexity. Tab cooling is a type of liquid cooling system which has improved cooling performance; the cooling performance to weight ratio of the system is also higher [19]. A study also reveals that tab cooling reduces the thermal gradient within the pack and improves the temperature distribution [20,21]. Hunt et al. [22] explored the effects of cell surface cooling and cell tab cooling, reproducing two typical cooling systems that are used in real-world battery packs. The work also reports that surface cooling using liquid coolants deteriorates the capacity of the cell three times higher than tab cooling due to thermal gradients being perpendicular to the layers of the surface. Several studies also reveal that tab (axial cooling) cooling provides a uniform temperature distribution and a smaller thermal gradient within the cell, and the limitation of such cooling is the tab area [23–26]. This can be overcome by increasing the thickness of the tabs and the number of the electrode stacks.

The design of a good thermal management system for a battery pack should consider both the overall temperature of the pack and internal thermal gradients. Considering the temperature gradient, it is concluded that tab cooling is better than surface cooling.

2. Experimental setup

The battery used in this work is a Samsung ICR18650-26JM. The cell chemistry of this battery is $LiNi\text{-}CoMnO_2$. The specifications of the battery are given in Table 1.

Table 1. Battery cell specifications.

Parameter	Specification
Dimensions	18 mm diameter and 65 mm length
Capacity	2600 mAh
Nominal voltage	3.60 V
Standard charging current	1.07 A (0.5 C)
Maximum charging current	2.15 A (1 C)
Standard discharging current	0.43 A (0.2 C)
Maximum discharging current	3.225 A (1.5 C)
Weight	47 mg

According to the specifications given by the manufacturer, the upper and lower limit of the cut-off voltage is given as 4.2 V and 2.5 V. Three cells were stacked in a series to form a battery pack as shown in Figs. 1 and 2. Figure 1 shows the solid model of the battery pack which is used for theoretical study. Figures 2a and 2b show the actual construction of the pack with and without cooling tabs. To make the pack, cells of similar capacity with the same OCV are stacked together. Three cells in series give a maximum of 12.6 V to a minimum of 7.5 V. As most of the conventional automotive electrical and electronic systems are 12 V systems, three cells were combined in series in this study. Using thermocouples, current sensor, BK Precision 8610 electronic load and Keysight data logger, the temperature, current and voltage are measured and stored during the charging and discharging cycle.

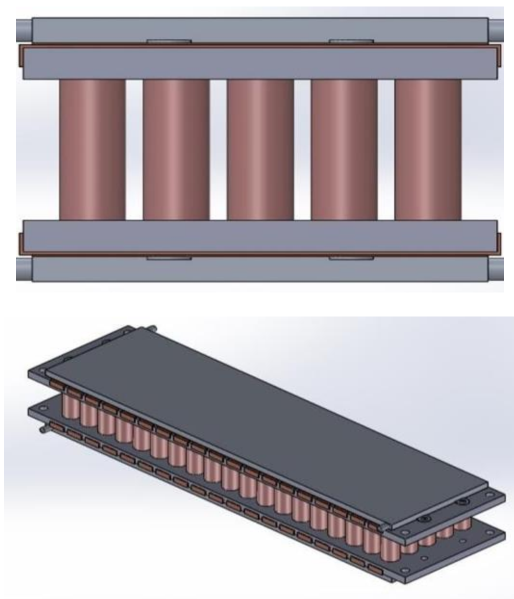

Fig. 1. CAD model of the pack.

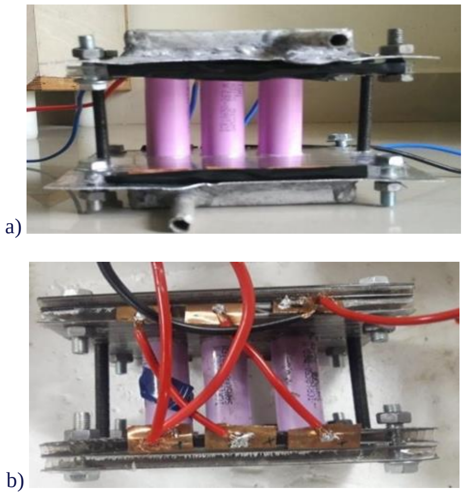

Fig. 2. Photographic view of the setup: (a) with cooling tabs; (b) without cooling tabs.

A two-way switch is used to ease switching between the charging and discharging state of the battery. An Imax B6AC lithium-ion battery charger is used to charge the batteries. It has a built-in balance socket in addition to configurable charge voltage output. Charging configuration can be programmed according to our requirements, using a software interface the charging data is acquired into the computer. The state of charge (SOC) is calculated using the coulomb counting method as given in Eqs. (1) and (2). Calculating the capacity of the battery ampere-hour (Ah) counting, or current integration, is the most common technique. This method employs battery current readings mathematically integrated over the usage period of charging or discharging and it is given by:

$$Capacity\ (\mathrm{Ah}) = \int_{t_o}^{t_0+\tau}(I_b - I_{loss})\ , \tag{1}$$

$$\mathrm{SOC} = \frac{\mathrm{SOC}_{to} + \int_{t_o}^{t_0+\tau}(I_b - I_{loss})}{Rated\ Capacity\ (\mathrm{Ah})}\ . \tag{2}$$

Figures 3a and 3b show the complete schematic and photographic view of the experimental setup used in this study. The battery packs are placed into a thermal chamber (isolation box) to replicate real-time conditions while charging and discharging the cells. To study the effect of cooling on the life of the cells, two sets of battery packs are made for each configuration and are tested under the same conditions to check the repeatability. Two configurations, without a cooling system and with tab cooling are tested. The tab cooling enclosure is manufactured inside the laboratory with available facilities and its physical properties are tested. A brief method of preparation of the tab enclosure is given here. To begin the fabrication of the tab cooling enclosure, a measured quantity of epoxy resin and hardener is added to a beaker. Nano-copper equivalent to 1% by mass of the total bled is added at a steady pace to the beaker and stirred continuously to make a blend. Followed by that, ripped strands of carbon fibre of 2% by weight are added to this mixture and stirred to make a blend. The first half of the prepared blend is poured into the mould which is already coated with a mould release agent. A woven carbon fibre sheet is placed on the mould and the remaining blend is poured into the mould. The prepared moulds are then placed inside the sintering furnace for 60 minutes and the temperature is set to 100°C. After 60 minutes the moulds are taken out and allowed to cool for five minutes before removing the casted component from the mould.

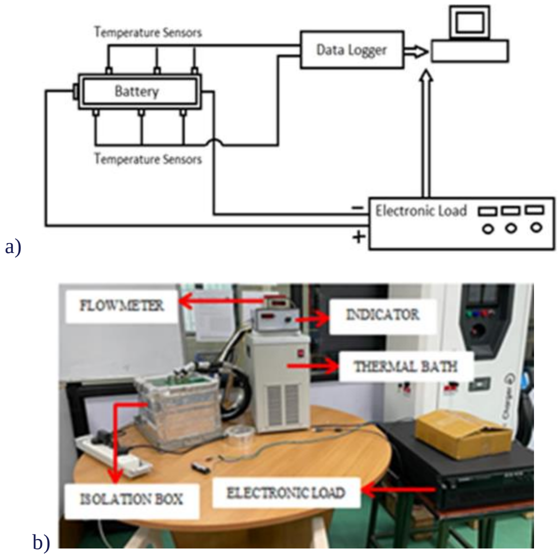

Fig. 3. Experimental setup: (a) schematic view; (b) photographic view.

The mineral oil that is used in electric transformers is used as a coolant for the battery pack. Mineral oil has good dielectric properties, chemical stability at high temperatures and moderate thermal conductivity. The coolant channel in the battery pack is supplied with mineral oil at a constant temperature of 35°C using a thermal bath. The flow rate can be varied from 0.5 lpm (litre per minute) to 2 lpm. The temperature was measured with a K type thermocouple. Thermocouples and sensors are connected to the Keysight 34970A data acquisition system. The flow rate of the coolant was measured using a turbine-type flow meter. The maximum possible error in the case of temperature and flowrate was calculated from the minimum values of the temperature and flowrate measured and the accuracy of the indicator as given by Holman (1973) [27]. The calculated error in the temperature and flowrate measurement was found to be 0.9 % and 0.5%, respectively.

The main factor in determining battery life is not only the battery temperature and discharging cycle but also the charging cycle as well. The research by Abousleiman et al. [28] compares the constant-current (CC) constant-voltage (CV) charging method against the time-pulsed charging method. The constant-current constant-voltage charging method is the most common approach that is used to charge li-ion batteries. The logic behind this approach is divided into two regions, a constant-current region followed by a constant-voltage region. The work by Xu et al. [29] suggests that both CC and pulse charging are good for fast charging and CV charging yields good efficiency.

The research by Musaliyarakam [30] compares different charging methods and enlists their advantages and disavantages.

The performance of each type of charger, namely battery resistance compensation (BRC), state of charge estimated technique (SET), fuzzy control based on battery temperature (FCST), fuzzy controller based on the active state of charge (FCASC) and sinusoidal ripple current technique (SRC) is compared with the conventional CC-CV type. BRC/FCASC can be used for low-power applications, where the battery packs are kept in a comparatively cooler area or where there is proper ventilation. FCST can be used if there is a tight tolerance for the temperature rise due to which the ambient temperature is close to the maximum operating temperature of the battery pack (55°C−60°C). SRC can be used for high-power/high-performance applications, where the battery charging efficiency plays a critical role along with the reduced charging time and battery temperature.

The charging method that was used in this work is a combination of CC and CV charging. Initially, the current supplied is high (1.5 A) until the voltage reaches 3.7 V, and subsequently migrates to CV until the voltage reaches 4.2 V (the charging current gradually decreases). After charging, the cells are left for two hours before starting the discharging cycle to allow the cells to reach thermal stability. The SOC for charging cycles was kept at 30% to avoid deep discharge.

2.1. Tab cooling design

Generally, electric vehicles use a separate cooling system which is linked with the vehicle's HVAC system to meet the operating temperature requirements of the battery pack. The HVAC system consumes energy from the battery pack [31]. Battery cooling system involves components of the HVAC system, coolant, coolant circuit, pumps and heat exchangers. These components consume a significant amount of energy from the battery and this study has not considered the energy consumed by the battery cooling system. The battery cooling system is an important subsystem of an electric vehicle as the optimal temperature range for the battery's efficient operation is between 15−45°C. Therefore, it is important to develop a highly competent battery cooling system to aid the high energy density cells. Tab cooling improves cell life but is difficult to implement. This is mainly because the surface that is the point of contact for the supply of electricity is also the surface that is supposed to transfer heat. Li-ion cells are made up of very thin layers of anode, cathode and separator rolled together or stacked together very close to each other to give the maximum energy density possible. These layers generate heat when charging or discharging due to the electrochemical reactions occurring in them. But the inner layers are generally hotter than the outer layers as they have a smaller surface area to dissipate heat. This temperature difference is the internal temperature gradient of the cell. Further, when the cell is cooled using either natural convection, air cooling or liquid surface cooling, cooling the curved surface of the battery cools only the outer surface. This further increases the internal temperature gradient of the cell.

A high internal temperature gradient either makes the inner layers much hotter than recommended or as the outer layers are much cooler than the inner layers, they end up providing most of the current supply. This results in the loss of available capacity of the cell and also accelerates the process of cell degradation. The primary objective of this work is to design and study the performance of a tab cooling system. Existing battery liquid cooling systems are either very intricate and segmented and difficult to manufacture or the ones which are easy to manufacture aren't very efficient. Moreover, ensuring that no leakage takes place adds to the difficulty and cost of manufacturing. To carry out the study, first, a battery pack with cylindrical lithium-ion batteries in series and parallel was modelled and analysed in ANSYS FLUENT. These include the initial model for 100 cells that gives 72 V and 25 A current ratings. The results are presented for a single battery, which could be representative of batteries in the battery pack.

To simulate the temperature distribution inside the cooling tab, a solid model of the enclosure is created. Sections were named as inlet, outlet, wall and battery. During mesh generation, certain surfaces need a sizing function to obtain a refined mesh to achieve accurate temperature distribution. The turbulence k–ε model is used for the analysis. The density, thermal conductivity and specific heat capacity of the composite material are taken as 1 760 kg/m^3, 3.91 W/(m K), 1 108 J/(kg K), respectively. The density of the composite is calculated based on the standard test piece of known volume and measured weight. The specific heat capacity is measured using the rule of mixtures and the thermal conductivity was calculated as per ASTM D5470-17 using a calorimeter. The governing equations used in this analysis are continuity, momentum, and energy equations. Coming to the solution step, the solver preferred for this analysis is the coupled solver with a second order upwind scheme. The number of iterations is varied till the convergence is reached.

The pack is designed specifically to achieve tab cooling in a battery pack that uses cylindrical li-ion cells. The cooling ducts of this design extract heat from the cell tabs more efficiently due to the larger contact area between the cooling fluid and cell tabs. The module was designed keeping in mind manufacturing constraints and addressing safety issues such as leakage of coolant. The tab cooling module is manufactured using composite material as it is an electrical insulator and has low thermal conductivity. Heat is transferred from the cell tabs to the coolant and the coolant is passed through the ducts or boxes.

3. Results and discussion

3.1. Simulation study

The flow and heat transfer analysis of the battery pack was done in the Ansys Fluent commercial software. The input parameters given for the analysis were: gravity in the negative Y-axis direction, inlet coolant temperature 303 K (30°C), inlet velocity 2 m/s and battery heat flux 1 100 W/m^2. The heat flux was calculated experimentally during the discharging of a battery in the calorimeter. For calculating the heat flux, a cell was discharged at 2 C inside a thermal bath filled with ethylene glycol and the temperature rise during the test duration was noted. Using Eqs. (3) and (4), the heat flux of the battery can be calculated. Figures 4 and 5 show velocity vectors in the enclosure and temperature distribution inside the battery tab. The theoretical study is mainly conducted to see whether the proposed design yields a better result.

$$\dot{q} = \frac{m_{eg} * C_{p\ eg} * (T_i - T_f) + m_{cv} * C_{p\ cv} * (T_{icv} - T_{fcv})}{t_d}, \quad (3)$$

$$Heat\ flux\ of\ the\ cell = \frac{\dot{q}}{Battery\ surface\ area}. \quad (4)$$

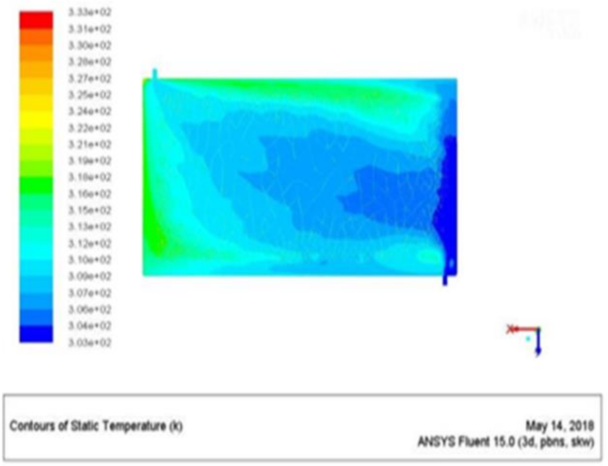

Fig. 4. Temperature contours in the coolant box.

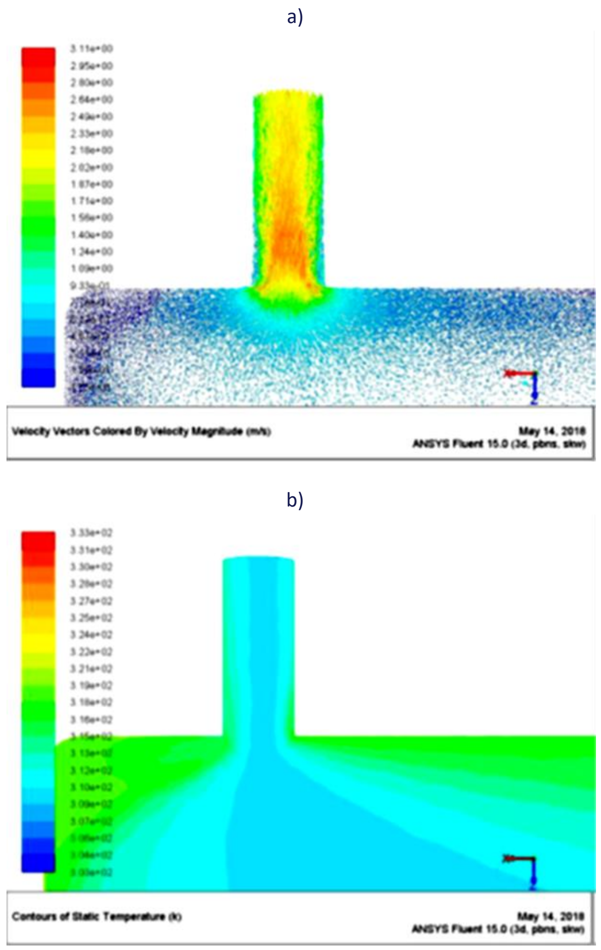

Fig. 5. Velocity vectors (a) and outlet temperature contours (b).

From the temperature contours it is observed that the overall temperature of the coolant remains about 313 K (40°C). Further, in the places where the temperature is high (shown in green), it is below 50°C. The average outlet temperature of the coolant is 38°C. From the velocity contours it is observed that the water loses its velocity as soon as it leaves the cylindrical inlet section of the coolant box and regains its velocity near the outlet region. As the results of the theoretical study are encouraging, battery tab enclosures are fabricated for experimental study.

3.2. Performance of battery pack without cooling

To benchmark the performance of the tab cooling, experiments were conducted using a battery pack without cooling tabs. It is very well known that the battery pack temperature will rise to a maximum level without the cooling system being incorporated. Heat is generated inside the spiral construction that involves multiple layers (known as a jelly roll) of the electrode assembly due to activation polarization, concentration polarisation and ohmic polarisation. If the generated heat is not removed from the cell/battery pack, the temperature of the cell rises. Without a cooling system, as the number of charging and discharging cycles increases, the temperature of the cell is also increased. The entire experiment is conducted at a thermal chamber temperature of 40°C. India is a tropical country, the central and southern parts of India experience hot weather for almost 9 months. The temperature reaches a maximum of 44°C during the peak summer. So, all the experiments are conducted at 40°C. A sample discharge profile (variation of voltage with respect to the capacity of the cell) of both packs with and without the cooling system is given in Fig. 6. During the entire course of the experiment, the battery was discharged at a 2 C current rating and the experiment was stopped after the battery reached 30% of the SOC to avoid deep discharge and damage.

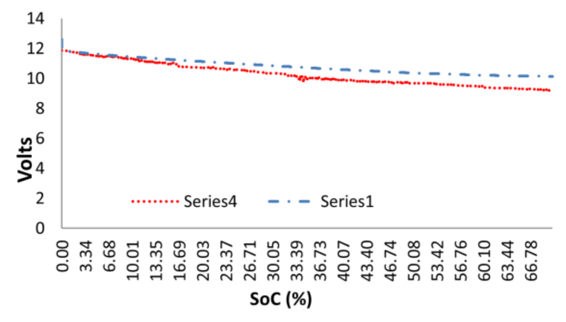

Fig. 6. Variation of discharge voltage with respect to capacity.

The temperature profile of the battery pack during the discharge test is given in Figs. 7 and 8. Figure 7 shows the temperature distribution of the surface of the cells. Each cell in the pack is installed with 6 thermocouples. A protocol is established to mount the thermocouples on the cells, i.e. locations of the thermocouples should be the same in all three cells of the pack. The locations are assigned numbers from 1 to 6 in each cell. T1 and T3 represent the locations of the thermocouple close to the positive and negative terminals of the cell. The average temperature at specific locations of the thermocouple is plotted in Fig. 7. From Fig. 8, it is evident that the peak temperature of the cells gradually increased as the cycles progressed; initially, it was close to 50°C for cells without a cooling system. While the middle regions of the cell registered a temperature close to 60°C during the tests, the thermocouples near the positive and negative tabs registered a maximum of 71°C and 69°C after reaching 700 cycles.

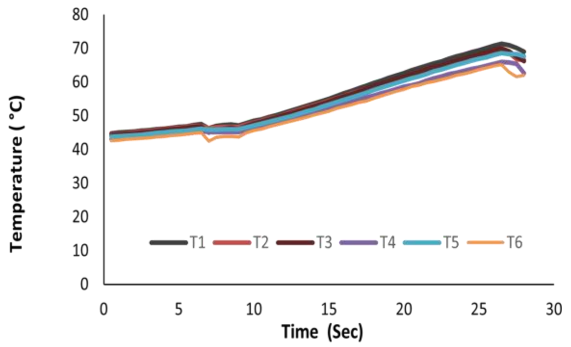

Fig. 7. Surface temperature at different locations on an 18 650 battery without a cooling system discharged at a rate of 2 C.

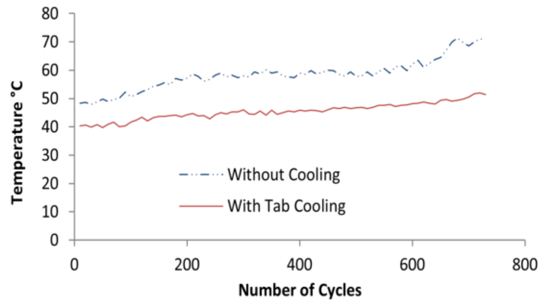

Fig. 8. Average peak temperature of the battery surface with respect to the number of cycles.

As mentioned earlier, during the loading cycle, cells are discharged till 30% of the SOC. When the cells in the pack are discharged at 2 C rating using a DC load, the duration of the test depends on the capacity (Ah rating) of the battery. It is also a known fact that the battery capacity fades with ageing (number of charge and discharge cycles executed). The capacity fading (effect of ageing) with respect to the number of charge and discharge cycles is studied and presented here. Figure 9 shows the comparison of test duration with respect to the number of cycles for both battery packs with and without cooling. For the pack without cooling, the pack reached 30% of the SOC within 25 minutes in the first few cycles and it was further reduced to 17 minutes at 700 cycles of charging and discharging. After 700 cycles the experiments were stopped as it represented a capacity loss of 30% of the nominal capacity. Generally, automotive battery packs will be replaced when there is a capacity fading of 30% of the nominal capacity. The rise in the discharge temperature and shortening of the test duration clearly represents the accelerated degradation of the cells in the pack without a cooling system. High discharge temperature also leads to a rise in internal resistance of the cells, which is also a sign of degradation.

3.3. Setup with cooling

The battery pack with a tab cooling system performed well when compared to the pack without a cooling system incorporated. Figure 6 very clearly shows that the discharge voltage of the tab cooling pack is higher than the pack without cooling by close to 1.5 V at the end of 700 cycles. It took almost 1 138 cycles to reach a 30% loss of initial capacity for the tab cooling pack, which is an indication of slower deterioration of the cells in the pack.

Figure 8 shows the peak temperature reached by the cells in the pack during the discharge. The maximum battery temperature was noted during charging and discharging cycles and the point at which the maximum temperature is registered with thermocouples (out of the six thermocouples) is taken as the maximum temperature of the cell and it is plotted in Fig. 8. As stated earlier, the temperature increased as the number of cycles increased. A maximum increase in temperature by around 5°C is registered with the tab cooling pack, whereas the maximum temperature rise by around 30°C is registered with the pack without a cooling system.

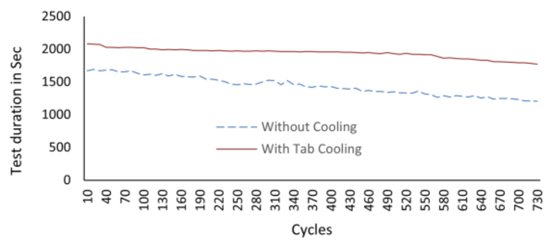

Fig. 9. Discharge time with respect to the number of cycles.

From Fig. 9, it is observed that the battery with a cooling system loses its power capacity much slower than the battery without a cooling system. This is primarily due to the heat extraction by the cooling system which allowed the temperature of the cells to remain below 50°C. The maximum temperature stays within 48°C for the battery pack with the cooling system. Further, it is also observed that the temperature of the battery starts increasing sharply when the circuit voltage drops below 9 V with both configurations. Concerning the capacity fading in Fig. 9, we can conclude that a 45% improvement in the cells' lifetime was achieved by implementing the tab cooling system.

4. Conclusions

The cooling system in battery modules is a very crucial sub-system of electric vehicles. Therefore, an attempt was made to study the performance of the tab (liquid) cooling system. A model was created and analysed in ANSYS, to confirm the merits of tab cooling.

For experimental validation, a miniature battery pack was made with 3 cells in a series. To compare the results of the cooling system, another battery pack with 3 cells in a series was made without a cooling system. Both the packs were charged and discharged repeatedly until a 30% loss in power capacity occurred.

The results of the pack with tab cooling show improvement in the performance and cycle life of the pack. A close-to-45% improvement in the cycle life of the cells was achieved with the tab cooling when compared to that of the pack without cooling.

Further, the results also show a marginal rise in the surface temperature of the cell in the tab cooled pack which ascertains the safe operation of the cells in the pack.

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