Efficient battery thermal management system design to ensure fast charging in extreme cold conditions

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Abstract: In extreme cold conditions, there are negative consequences on battery life due to extremely slower rate of chemical reactions, resulting in lower charging rates. Therefore, an efficient battery thermal management system is required to ensure temperature optimization is low which may also result in charging. In best of authors understanding, there is hardly any research being carried out in this direction. In this paper, an Intelligent Optimization framework combined with computational fluid dynamics (CFD) shall be proposed to optimize the heating method accuracy so as to maintain the uniform and desired temperature across the battery for ensuring smooth and quick charging. Battery pack model shall be designed in CFD platform and the thermal analysis shall be carried for given set of conditions (such as constant heat source, air flow rate, air temperature). Based on the obtained set of analysis samples, a model shall be formulated illustrating relationship between the minimum temperature output and the inputs (air flow rate, air temperature, etc.). The minimum temperature output shall be maximized using NSGA II so as to determine the optimum set of input conditions (air flow rate, air temperature, etc.). The battery pack simulation revealed that thermal system utilizing a liquid medium is more effective than air medium. Future research directions shall be discussed in the end.

Keywords: Thermal management; Cold conditions; Fast charging;

1. Introduction
In the last two decades, Lithium-ion Batteries have grown to be the primary choice of energy storage devices and are widely utilized in many of the world’s most prominent industries, like the tech industry and, now, the automobile industry. With the advent of electric vehicle technology and the growing number of companies initiating electric vehicle (EV) programs, production and demand of Li-ion batteries has never been higher and only grows every day [1]. In 2016, the average price of Li-ion batteries was $273/kWh – a reduction of nearly 73% since 2010. In 2017, ‘Bloomberg New Energy
Finance’ projected the annual demand for Li-ion Batteries for EV Production to grow to 408 GWh by 2025, and 1293 by 2030 [1]. This rapid growth is indicative of the automobile industry’s transformation to sustainable transport system, especially in the light of the devastating effects of global warming due to pollution [2]. The transformation has been possible due to ever-advancing battery technology, which has allowed automobile manufacturers to boast superior battery range and charging rates in their vehicles. Both of these parameters Battery Range and Charging Rate are an important concern for these companies since many consumers experience ‘Range Anxiety’, a fear that their vehicles may run out of battery while driving with no nearby charging stations – a primary reason behind the slower adoption of EVs as compared to internal combustion engine vehicles (ICEV) [2]. While having access to a great charging infrastructure is necessary for tackling this issue in any market, it is also important to innovate new ways of improving the power-to-weight ratios of Li-ion batteries in EVs and its charge-discharge cycles to increase efficiency in batteries.

Current Li-ion battery technology has been a great benefactor for enabling EV technology, however the power provided by such a reliable battery is anything but constant. Given the ambient environment, a battery certainly behaves differently in various conditions. This change in the behaviour of battery performance can be observed by monitoring it under varying temperatures. Specifically, a battery’s performance in a cold environment drops remarkably. In a study, Li-ion batteries were observed to lose 10-20% of charge at temperatures ranging Between -10°C to 0°C, and up to 40% when the temperature drops below -20°C [3]. This is due to slower kinetics of the internal chemical reactions of the battery. Consumers in areas with cold climatic conditions experience a drop in battery range and thus, on-average require more charging time. For such conditions, having a thermal-management system becomes a necessity for batteries to operate efficiently. Such a system may use fluid applications, wherein the fluid would actively fulfil a battery’s heating demands. This would require an outer structure with a fluid inlet and outlet port surrounding a pack of batteries, wherein the fluid flux would carry out excess battery heat in a cyclic fashion [4]. A thermal management system would allow the batteries of the EVs to last longer under a single charge by ensuring that they operate at an optimal condition. Current research into battery thermal management systems have a major focus on reducing the effects of high temperatures, as compared to the effect of sub-zero temperatures on batteries, and thus the paper aims to build and simulate a battery system that can endure such cold environments.

Its batteries operate at an optimal external temperature. This is crucial for EV manufacturers as any substantial battery range improvements will give them an opportunity to gain competitive ground over other existing EVs in the market. Consumerism and efforts towards a Sustainable Future win at the end, and for this reason the paper proposes a viable thermal management system utilizing fluids that may be developed further and deployed in EVs. The objective of the study is to test and evaluate different types of heating methods that allow the battery to function optimally, and thus giving better performance for EVs.

2. Problem Formulation
The current study was conducted in order to devise rectifications and other enhancements to existing fluid-cooling processes for lithium-ion battery packs. Figure 1 shows the 3x4 Battery Pack that was used for the computer simulation; it consists of 3 rows of four parallel-connected batteries. The casing used for the 12-battery pack is made of aluminium. The thermophysical properties, dimensions and heat generation model of the battery cell has been extracted from past research.

The present study was focused on suggesting improvements on air cooling strategies for lithium ion battery pack. A 3X4 battery package (3 lines in series, each line with 4 cells in parallel) as shown in the Figure 1 was chosen for the analysis. The entire battery pack was enclosed in a casing of aluminium as in Figure 1. The dimensions, Thermophysical properties and heat generation model of the cell was taken from previous literature [34]. The values are tabulated in Table 1.
Figure 1 3D Model of Battery Cell Pack, consisting of 12 cells in a case.

Table 1. Thermophysical Properties of Lithium-Ion Cells.

| Parameters                     | Value             |
|--------------------------------|-------------------|
| Rated Voltage                  | 3.2 V             |
| Rated Voltage                  | 1.35 Ah           |
| Equivalent Density             | 2018 Kgm⁻³        |
| Equivalent Specific Heat       | 1282 JKg⁻¹K⁻¹     |
| Volume (V)                     | 1.654 x 10⁻⁵ m³   |
| Thermal Conductivity           |                   |
| Radial Direction               | 0.9 Wm⁻¹K⁻¹       |
| Axial Direction                | 2.7 Wm⁻¹K⁻¹       |

Heat dissipated during the cell discharge can be calculated using the Bernadi Equation:

\[ \dot{q} = \frac{1}{V} \left( I^2 R + I T \frac{dU}{dT} \right) \]

\( \dot{q} \) ~ Volumetric Heat Generation per Second.

V ~ Volume of Individual Cell.

I ~ Discharge Current.
R ~ Internal Resistance of the Cell.
T ~ Temperature
U ~ Open Circuit Voltage of Cell.

Volumetric Heat Generation for various cell discharge rates are shown in Table 2:

| Discharge Rate | Volumetric Heat Generation |
|---------------|---------------------------|
| 1C            | 5318 Wm\(^{-3}\)         |
| 2C            | 19452 Wm\(^{-3}\)       |
| 3C            | 42400 Wm\(^{-3}\)       |
| 4C            | 74163 Wm\(^{-3}\)       |

Case 1
A Battery Pack of 18650 Lithium-Ion Cells was simulated under a varying set of cold temperatures, specifically at 0 °C to -5 °C at increments of 1 °C.

It was observed that decreasing temperatures result in a drop in pressure. A drop in pressure results from the fact that the cells expand slightly as the temperature decreases, which then negatively affects cell performance and charging rates.

At colder temperatures, battery inefficiency increases drastically due to increased internal resistance and lowered energy capacity. At a temperature of -10 °C, a battery supplies only 50% of its optimal capacity at 25 °C to 35 °C. The proportional decrease in energy capacity depends on the battery chemistry of the cells[5].

Figure 2. SOC curves for 0 and 5°C temperature.
The adjacent graph indicates how the state of charge of a battery decreases at lower temperatures, thus affecting its energy capacity. This leads to an increase in the discharge rate of the battery and, hence, a poor performance of the battery at lower temperatures[8].

![Battery Energy Capacity vs. Temperature](image)

**Figure 3.** Battery capacity and temperature.

The performance of Li-ion batteries is clearly reduced at lower temperatures. For example, it has been reported that for the same current, the available energy of a Li-ion cell at 20 °C is 60% of the room-temperature value [17]. Graph.1 shows the test results and Wh characteristics of an actual HEV battery at four different ambient temperatures (25 °C, 0 °C, 10 °C and 20 °C) and three discharging currents [18].

**Case 2**

The battery pack was simulated under higher temperatures via two methods: Air heating method, and fluid heating method.

Heating by air is a common method employed in electric vehicles due to its minimal design needs. A battery thermal management system utilizing hot air is designed in a closed system containing heaters, fans, flow channels, and batteries, in such a manner that keeps heat loss at a minimum. This is a convection heating method wherein the heater turns electrical energy to thermal energy that is then transferred via convective flow of air by fans to the batteries. The hot air flows between the battery pack wall and external battery surface and through an inlet and outlet valve. This circulation of air makes it an efficient system of maintaining constant heat transfer to the batteries.

The conclusion was that the best cooling performance is achieved. The heating power of air was found to be 963W, with a maximum heating of (0.703)°C/min.

Forced-air convection cooling can therefore moderate the temperature increase inside a battery pack. However, Nelson has demonstrated that past a certain temperature point (66 °C), it is difficult to cool a battery via air cooling because of the low conductivity of air [14]. Thus, at reasonable discharge rates
and operating temperatures (<60 °C), cooling is advised[15]. Under very harsh conditions (>60 °C), a liquid system is preferable.

Case 3

![Energy Efficiency of Li-ion Batteries at Room Temperature](image)

**Figure 4.** Energy efficiency at various charging rates.

\[
\text{energy efficiency} = \frac{\int (V_{bd} \times I_{bd}) \, dt}{\int (V_{bc} \times I_{bc}) \, dt} \times 100
\]

- Vbd → Voltage during battery discharge
- Ibd → Current during battery discharge
- Vbc → Voltage during battery charging
- Ibc → Current during battery charging [7].

The above graph portrays how the energy efficiency of the charging process drops significantly as the charging rate of the battery increases. It’s important to point out that battery voltage is higher during the fast charging process as compared to the discharging process. During discharging, a nominal voltage of 3.7V per cell is maintained, while it is higher than this during fast charging. During fast charging, however, it is important to maintain control of certain battery parameters such that overcharging or excessive heating in the battery is avoided. In the experiment, the battery was heated to a range of 25°C to 35°C, and to help avoid damages to the battery during the charging process, a maximum battery voltage of 4.2V per cell was maintained.

For heating via liquid, the heating power was 15.7W and maximum heating rate was (1.13)88°Cmin⁻¹[4]. Compared with air, liquids are a more efficient medium of heat transfer since the thermal conductivity and the convective heat transfer ratio is higher in liquid based systems. Liquid cooling/heating for battery packs can be achieved using two different approaches: surrounding the modules with a jacket/plate containing streams of heated/cooled liquid or immersing the modules in direct contact with a cooling/heating fluid [16,19]. The heat transfer liquid could be water, oil, acetone, glycol, or even a refrigerant. In [16,20], Pesaran compared liquid cooling with air cooling. Based on his observations, he suggested that air-based systems are less difficult to set up but less efficient than a system using liquid cooling/heating. The simulation results indicated that liquid cooling is generally
more efficient than the PCM strategy, although PCMs engender a more uniform temperature behaviour. Surprisingly, the authors observed no significant influence of the Reynolds number in the case of liquid cooling, but only in the air-cooling case.[21]

3. Conclusion
Heating via liquid was found to be more efficient than heating via air, since the heating rate was observed to be higher and a more uniform distribution of heat was maintained. Moreover, there are minimal maintenance costs in the heating via liquid method as compared to heating via air method. The battery charged at an optimal rate between 25 °C to 35 °C. The battery capacity was severely affected in sub-zero temperature range. These work was aimed at understanding the behaviour and reaction of various important parameter at sub-zero temperature range. The future scope for these work would be to optimize the battery performance for sub-zero temperature conditions using sophisticated algorithms such as support vector machine, genetic algorithm and neural networks [22-25].

References
[1] https://data.bloomberglp.com/bnef/sites/14/2017/07/BNEF-Lithium-ion-battery-costs-and-market.pdf
[2] http://e-mobility-nsr.eu/fileadmin/user_upload/downloads/info-pool/the_phenomenon_of_range_anxiety_elvire.pdf
[3] Sheehy.P, Giles.C, Johal.H, “Electric Vehicle Deployment Potential in the Yukon Territory”, World Electric Journal Vol. 8, Page WEVJ8-0709.
[4] https://www.researchgate.net/publication/330411079_A_review_of_the_estimation_and_heating_methods_for_lithium-ion_batteries_pack_at_the_cold_environment
[5] https://batteryuniversity.com/learn/article/discharging_at_high_and_low_temperatures
[6] https://ieeexplore.ieee.org/document/8493503
[7] https://ieeexplore.ieee.org/abstract/document/1401439
[8] https://www.mdpi.com/1996-1073/9/9/720/htm
[9] https://www.researchgate.net/publication/300809211_Energy_Efficient_Battery_Heating_in_Cold_Climates
[10] https://nur.nu.edu.kz/handle/123456789/852
[11] https://www.mdpi.com › pdf
[12] Al-hallaj S, Selman JR. Thermal modeling of secondary lithium batteries for electric vehicle/hybrid electric vehicle applications. J Power Sources 2002;110:341–8.
[13] Wang T, Tseng KJ, Zhao J. Development of efficient air-cooling strategies for lithium-ion battery module based on empirical heat source model. Appl Therm Eng 2015;90(Nov):521–9.
[14] Nelson P, Dees D, Amine K, Henriksen G. Modeling thermal management of lithium-ion PNGV batteries. J Power Sources 2002;110(2):349–56.
[15] Wu M, Liu KH, Wang Y, Wan C. Heat dissipation design for lithium-ion batteries. J Power Sources 2002;109:160–6.
[16] Pesaran AA. Battery thermal management in EVs and HEVs : issues and solutions. In: Adv automot battery conf; 2001.
[17] Bugga R, Smart M, Whitacre J, West W. Lithium Ion batteries for space applications. In: 2007 IEEE aerosop conf; 2007. p. 1–7.
[18] Jaugemont J, Boulon L, Dubé Y, Poudrier D. Low temperature discharge cycle tests for a lithium ion cell. In: Veh power props conf; 2014; p. 1–6.
[19] Huo Y, Rao Z, Liu X, Zhao J. Investigation of power battery thermal management by using mini-channel cold plate. Energy Convers Manage 2015;89(Jan):387–95.
[20] Pesaran AA, Burch S, Keyser M. An approach for designing thermal management systems for electric and hybrid vehicle battery packs preprint. In: Fourth veh therm manag syst conf exhibit, no. January; 1999.
[21] Liu R, Chen J, Xun J, Jiao K, Du Q. Numerical investigation of thermal behaviors in lithium-ion battery stack discharge. Appl Energy 2014;132 (Nov):288–97.

[22] Garg A, Ruhatiya C, Cui X, Peng X, Bhalerao Y and Gao L, 2020 Journal of Electrochemical Energy Conversion and Storage, 17(2). DOI: 10.1115/1.4045194

[23] Ruhatiya C, Gia Bao P N, Quan T L, Tho Q T, and Xinyu L, 2020 Energy Storage. DOI: 10.1002/est2.130

[24] Ruhatiya C, Shaosen S, Wang C T, Jishnu A K, and Bhalerao Y, 2019 Energy Storage, p.e111. DOI: 10.1002/est2.111

[25] Ruhatiya C, Singh S, Goyal A, Niu X, Nguyen H, Ngoc T, Nguyen V H, Tran V M, Phung L E, Loan M, and Garg A, 2020 Journal of Electrochemical Energy Conversion and Storage, 17(1). DOI: 10.1115/1.4044358