Designing and CFD Analysis of Two- Wheeler Electric Vehicle Battery

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Abstract

The transition to electric mobility, owing to its proposition as a solution to the environmental qualms of rising levels of pollution due to the utilization of conventional sources of energy (fossil fuels), has directed the attention of researchers to the main energy storage system of the electric vehicles that is batteries. Due to their efficient peak and average power delivery, batteries are the preferred choice for energy storage. With Lithium-ion chemistry proving to be an efficient battery technology in terms of energy density, specific power, safety, durability, and reduced emissions; the requirements for their optimum operation include a temperature range of 15°C-35°C and a uniform temperature profile, which in turn affects the vehicle performance are a cause of concern. This underscores the importance of a design of an effective battery thermal management system (BTMS). A BTMS is tasked with maintaining a fixed range of temperature throughout the battery operation, thus enhancing its life and efficiency. A variety of BTMS designs have been presented based on different types of medium, power consumption, and thermal cycle. The objective of this work is to analyze one such BTMS for 18650 arrangements of cells in a battery module using CFD and utilize the results of the analysis to propose the optimum BTMS for enhanced performance of the battery module.

The CFD analysis has performed the assessment of the Spiral cooling method using ANSYS Fluent in the BTMS. The analysis of the Spiral cooling method through the battery module can give a better insight into changing the packing arrangement of cells and positioning of active or passive thermal management systems.

Keywords: Electric Vehicle Battery, BTMS, CFD. Analysis.

Introduction

Rising pollution levels, climate change, and global warming are the pressing issues that have made the requirement of alternate energy source utilization imperative. The transition to electric vehicles is the current focus as far as the automotive industry’s contribution is concerned. Batteries are the most feasible among the various alternative energy storage systems, owing to their efficient peak and average power delivery rates. Out of the several existing battery technologies, the Lithium-ion battery technology is primarily used because of its high specific power, energy density, longer life cycle, reduced weight, and absence of memory effect. However, the thermal sensitivity of these batteries, significantly impacts their overall performance and durability. The operating conditions are limited to a narrow temperature range of 15°C and 45°C for optimum operation of Lithium-ion battery systems, and the temperature variation should not exceed 5°C for a multi-cell module. There are several aspects of battery’s safety which can lead to further degradation in battery life and performance such as suboptimal performance due to sluggish chemistry during low temperature battery operation, the ambient temperatures causing the battery to exceed the upper temperature limit coupled with capacity fade, and electrical imbalance and/or self-discharge. Temperature uniformity is desirable to prevent thermal runaway and associated implications. Therefore, an appropriate thermal management for the battery systems is required. The emphasis on the requirement of an effective Battery Thermal Management System (BTMS) to enhance the electric vehicle performance, which necessitates increasing the number of cells and energy density, results in rise of the battery temperature. An efficient BTMS is essential to avoid degradation of the battery overtime and maintenance of optimal performance capability. In this study, development of a cooling system for the battery is emphasized for acknowledging the adverse effects of exceedingly high temperature in the battery and with regards to safety. BTMS is tasked with maintaining the appropriate temperature range by removing heat from the battery at higher temperatures, adding heat during low temperature conditions and insulation to maintain uniformity of temperature distribution in a battery module. One approach has been utilized to accomplish the mentioned task resulting in the classification of BTMS according to their medium of cooling (liquid), type of fluid used and inlet velocity. As a result of comparison between two fluids (Propylene-Glycol-water mixture and Ethylene-Glycol-water mixture) at inlet velocity of 0.1 m/s and 0.3 m/s temperature and pressure is calculated. The indirect liquid cooling system is better in comparison to air cooling systems for handling high heat dissipation rates in EV batteries. The liquid cooling BTMS have a better cooling efficiency and capacity, and lesser noise generation, but these are bulky and consume more energy. Air cooling BTMS are comparatively light, cheap, and reliable with a simpler and compact design. This has encouraged their adoption in Nissan Leaf, Honda Insight, Lexus and Toyota Prius despite their shortcomings which include increased energy requirement and noise. Improvisation in the air cooling BTMS design can help augment the overall performance of the automobile. The design optimization of air cooling BTMS could be accomplished by different arrangements such as modifying the packing arrangement in Parallel, staggered, cross, dense, line, rectangular, square, hexagonal and ringed arrangements and modifying the air flow channel as tilting the case by 5^{o}c to reduce the air flow drag, arranging the batteries horizontally, using two sided cooling with wide unequally spaced channel, employing reciprocating airflow channel, directing the airflow via thin ducts, baffles, inlet plenum, novel U-Type channel, Z-Type channel and J-Type channels.

Therefore, in this paper the design and analysis of an effective system for thermal management in battery arrangement of electric vehicle according to Indian climatic condition is undertaken. The objective of this study is to analyze the active cooling BTMS performance of Lithium-ion battery array systems for arrangement of cells in a battery module by using ANSYS Fluent.

Previous Thermal Management and Battery Coolant Flow Studies

Previous analyses of thermal management systems (TMS) typically seek to examine a proposed improvement by building a vehicle and thermal system model to characterize the system response and range benefits. These studies are typically limited to investigation of a single system (or subsystem) with respect to a baseline, a single mode of operation or neglect active battery cooling or heating. Additionally, the extension of this analysis to a battery coolant flow study and optimization is crucial to understand temperature distributions insides cells, a key indicator of long-term cell health, temperature difference within the pack, max battery temperature, and pressure drop inside of the cooling solution. Previous studies on specific battery cooling solutions focus narrowly on a single or small grouping of cells, ignore thermal interface materials (TIM) at key interface points, and ignore fins where applicable in typical module design. These studies are limited to optimizing a single flow configuration, geometry, or cold plate concept without concern for the broader pack implications.

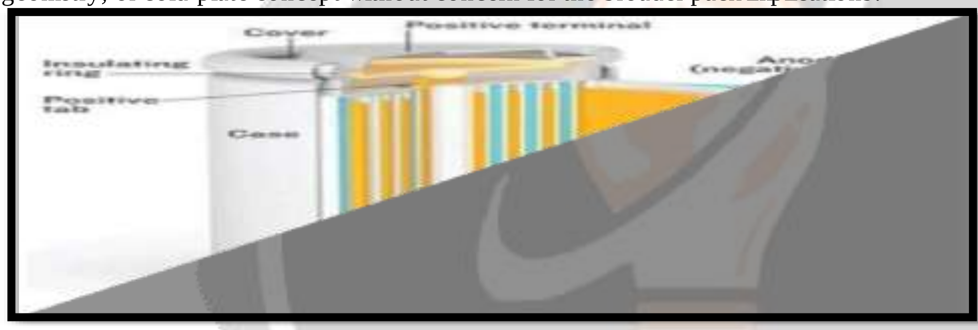


Figure - 1.2.1: Lithium-ion cylindrical cell composition

Figure - 1.2.2: Lithium-ion pouch cell composition

However, LIBs are not perfect technology and need some improvement to be working safely. The main LIBs system (BTMS) is essential. A capable BTMS prevents battery overheating and estimates remaining battery life so that the battery works efficiently and provides stable operating conditions problem is related to thermal issues. These batteries are susceptible to temperature. Having a higher or lower temperature than the recommended temperature can lead to problems and thermal impacts in the cell. That can affect the battery lifetime, capacity,

operational performance, or in the worst scenario overheating the cell and at which point the cell catches fire, or it explodes. Therefore, a good battery thermal management (BTMS) is essential. A capable BTMS prevents battery

overheating and estimates remaining battery life so that the battery works efficiently and provides stable operating conditions.
The lithium-ion has several cell formats at the market, and the most common ones are the cylindrical, prismatic, and pouch cells. The various cells have different chemistries, designs, and configurations and used for various applications, but the general components that are used in the LIBs battery are similar. The lithium cells can be used as primary and secondary batteries. The primary batteries are based on non-electrically reversible chemical reactions that cannot be recharged and generally used for the electronic, while the operation of secondary batteries is based on reversible electrochemical reactions, which makes them rechargeable. The Specific energy of LIBs makes them more suitable for the energy storage systems and other applications such as EV and smaller devices that required consuming power without being connected to a powerline.

Lithium-Ion Batteries Common Chemistries

The Lithium Iron Phosphate (LFP), Lithium Nickel Manganese Cobalt Oxide (NMC), and Lithium Nickel Cobalt Aluminum Oxide (NCA) are the most commonly used cell chemistries. They are all known by their high specific power/energy and high performance. Table 1 and Figure: 1.3.1 below present the technical differences and similarities of these cell types.

For the C-rate, it is a measure of the rate at which a cell is charged or discharged relative to it is maximum capacity, and this described in Equation 1. If a cell been discharged with 1 C-rate, it means that the cell will be discharged in 1 hour, and a 2 C-rate the cell will be discharged in 0.5 hours or 30 min. Equation for battery rate is mentioned below.

$$Crate\ (h{-}1) = I\ (A)\ Ccapacity\ (Ah)$$

Problem Statement

In the future, more LIBs for energy storage systems are going to be installed. Many of them have been used for the integration of renewable power generation (e.g., PV solar and wind power), and more projects are ongoing and planning, which covers most of the energy storage services in both grid and microgrid applications. Many factors should be taken into consideration regarding the battery system before installation, and they are; safety concerns, cost, life cycle, temperature-related issues. The thermal effects of LIBs and optimized thermal management are critical for safe and reliable operation of LIBs systems. The performance and life span of LIBs are significantly affected by its thermal behavior associated with the cyclic processes and operating temperatures (Ouyang, o.a., 2019). A clear understanding of the thermal properties of LIBs and proper thermal management is essential for system design, ensuring safety, and maintaining good battery performance. This report focused on the commercial LIBs and their BTMS, mainly based on grid/microgrid LIB energy storage application e.g., Vattenfall's LIB energy storage systems and corresponding BTMS. The purpose of this work is to investigate the status of BTMS technologies applied for stationary lithium-ion BESS and develop a model to study the thermal behaviour of the cell. In this study, a model for a battery pack with BTMS using liquid cooling is also developed, and the performance of the cooling system was analysed.
The investigation focused on: Status of thermal management technologies applied for stationary lithium-ion battery.

Developing a battery model and a thermal model for the battery cell to evaluate the thermal performance of LIBs.

Integrate the battery and thermal model into the battery pack and use it for modelling of BTMS to investigate the thermal behaviour of the LIBs system using liquid cooling.

Literature Review

The literature review was conducted to get more understanding and more profound knowledge about the development of LIBs, their thermal issues, and thermal management technologies. The literature was collected from a reverent search engine, mainly from Science Direct, IEEE Xplore, and ResearchGate. The relevant keywords that have been used in different constellations are battery models, BTMS, BESS, and electric vehicles. The literature was reviewed regarding BTMSs available in the market to find a suitable system that can be applied for stationary BESS.

Ev Battery Cooling Methods

Electric vehicle batteries and their associated cooling systems have been extensively studied in the literature, as previously exhaustively reviewed in References. The goals of these past studies typically are to optimize existing cooling methods, establish alternate cooling methods, and investigate battery cell architectures.
EV battery cooling methods investigated in the literature include air cooling, liquid cooling, direct refrigerant

cooling, and immersion cooling. Air cooling ducts air either from the ambient (passive) or conditioned from the cabin vapor compression cycle (VCC) (active) through the battery. This approach suffers from low cooling capacity due to the poor thermal conductivity of air and the size of the air ducts reduces the effective battery density, both contributing to a decreased range for the finalized system. Thus, air-cooled batteries are typically found in shorter range electric vehicles. Longer range BEVs typically implement liquid cooling due to more favourable heat transfer characteristics that allow for a denser cooling solution. In the case of a direct liquid cooling solution, coolant is brought as close as possible to the battery for optimal heat transfer performance while an indirect solution places a cold plate along the bottom of the entire battery system's length while providing fins to interface with the battery. Further evolutions of direct liquid cooling, seeking improved heat transfer performance to ensure cell safety under extreme conditions, are two-phase direct refrigerant and immersion cooling concepts. Direct refrigerant systems bring two phase refrigerants to the battery via a cold plate and manifold system, like a direct liquid cooling solution, and evaporate the refrigerant. A more uniform and higher capacity cooling are associated with two-phase flow of the refrigerant across the battery cold plate. Passive two-phase immersion cooling submerges the EV battery in dielectric fluid that boils in response to heat rejection from the battery. Currently, these two-phase cooling methods have limited implementation in the consumer market. The current study focuses on ITMS architectures having a secondary loop, indirect liquid cooling system for the battery. Analysis across a wide range of ambient conditions to examine their performance in heating and cooling modes has been identified as a gap in past research.

Phase Change Material (Pcm)

PCMs were first used for BTMS by Hallaj and Selman. The phase change material has high latent heat and acts as a heat sink during battery discharge. When the cells are on standby, the PCM releases heat to the cells and the environment. The PCMs used for thermal management have a melting point in the optimum performing range of lithium cells. This way the cell temperature will stay at the right temperature for a long time. All cells are one of the manufacturers of PCM for battery thermal management. Their product consists of paraffin (as PCM with a melting range of 32-38oC) mixed with graphite flakes to enhance thermal conductivity. The graphite flakes will also create a semi matrix block which will contain the paraffin particles. Hence, even when the paraffin is melted, it stays within this matrix and the whole composition maintains its' solid form. The other advantage of solid PCM is that they also act as shields, in case one cell enters thermal runaway.
However, there is a downside to PCM too. If the batteries operate for a long time, or the ambient temperature is too high, then the PCM might completely melt and due to its low thermal conductivity, even act as thermal barriers. If the ambient is too cold, the PCM will add thermal mass to the modules and make it more difficult for the cells to reach the right temperature.

Figure - 3.4.1: Battery module with PCM

Overall, PCM can be the best passive solution for modules with a low operating rate or combined with active cooling (e.g., indirect liquid cooling) for higher operating rates and extreme ambient temperatures.

Structural Analysis

Structural analysis is probably the most common application of the finite element method as it implies bridges and buildings, naval, aeronautical, and mechanical structures such as ship hulls, aircraft bodies, and machine housings, as well as mechanical components such as pistons, machine parts, and tools.

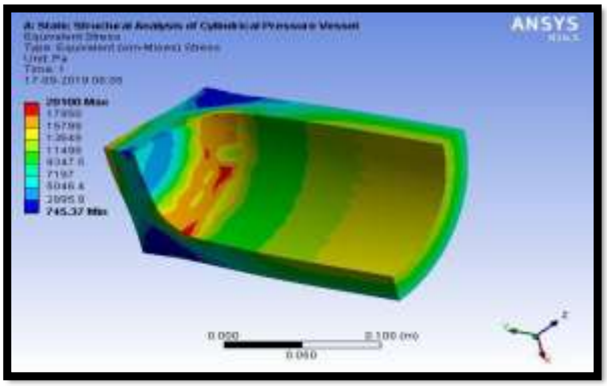


Figure - 6.2.1: Structural Analysis in ANSYS

Modal Analysis

A modal analysis is typically used to determine the vibration characteristics (natural frequencies and mode shapes) of a structure or a machine component while it is being designed. It can also serve as a starting point for another, more detailed, dynamic analysis, such as a harmonic response or full transient dynamic analysis. Modal analyses, while being one of the most basic dynamic analysis types available in ANSYS, can also be more computationally time consuming than a typical static analysis. A reduced solver, utilizing automatically or manually selected master degrees of freedom is used to drastically reduce the problem size and solution time.

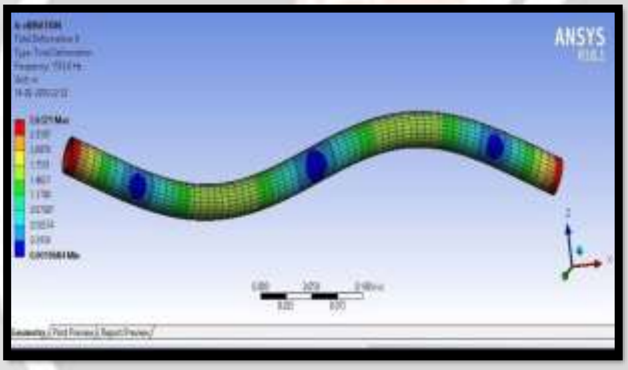


Figure - 6.2.3: Modal Analysis in ANSYS

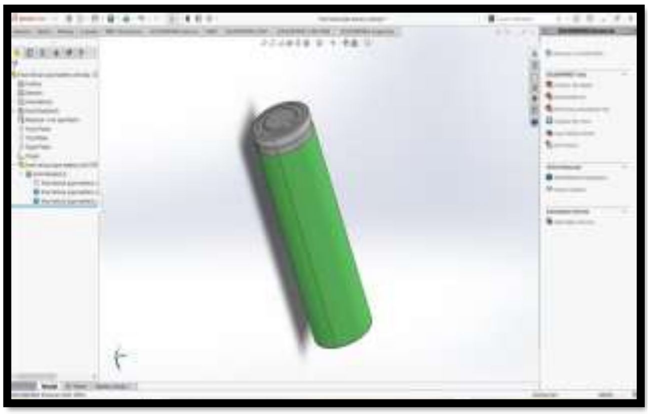


Fig - 7.1: Design of 18650 Cell

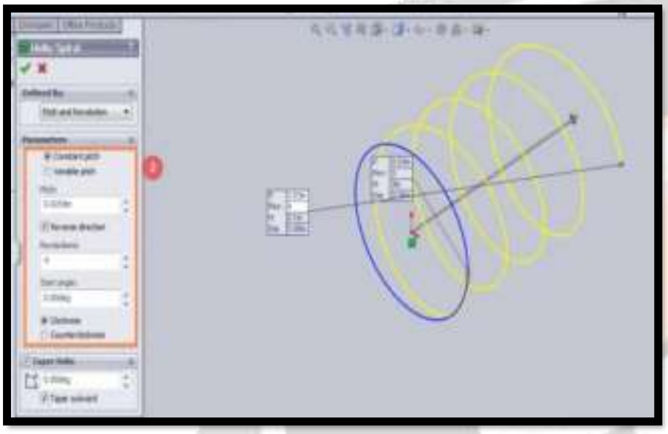
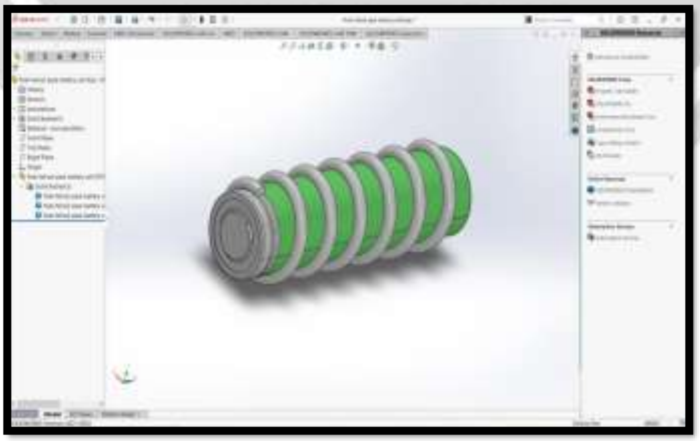


Fig - 7.2: Design of Helical Spring



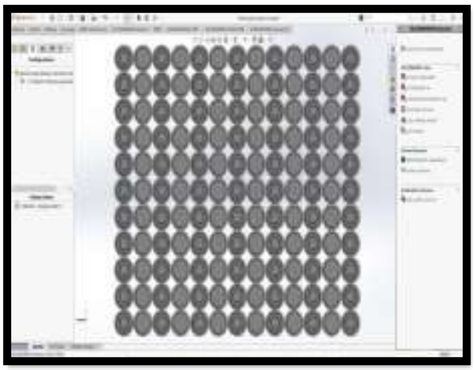


Fig - 7.4: Top view of Battery Pack

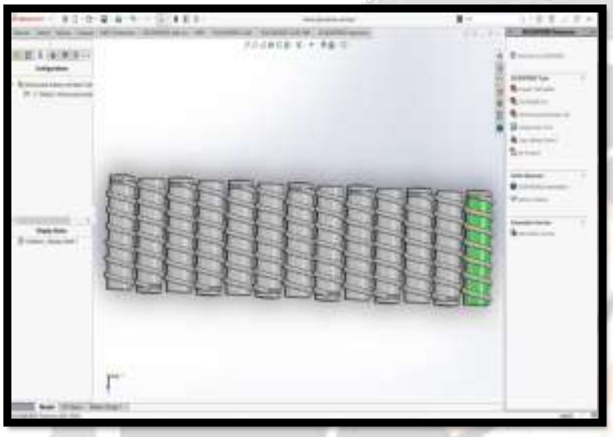


Fig – 7.5: Side View of Battery Pack

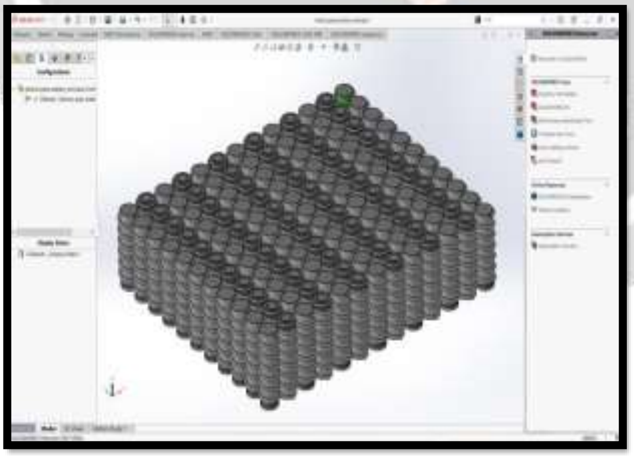
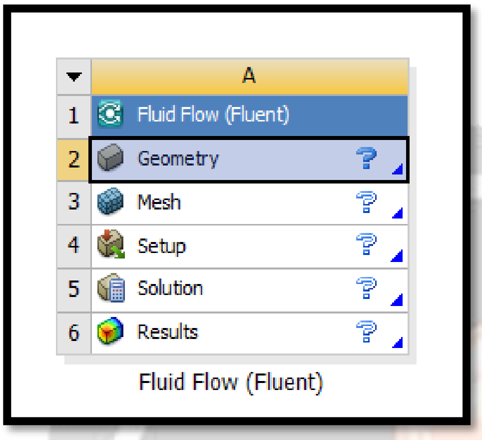


Fig – 7.7: Isometric View of Battery Pack

CFD ANALYSIS OF SINGLE 18650 BATTERY CELL USING ANSYS

- To import the CAD file in the Ansys Fluent, first convert the CAD file into IGES format.
- Right-click on 'Geometry' and import the CAD file in the geometry section of Ansys Fluent.
- After importing, right-click on geometry and open the design with 'Design Modeler'.
- In the design Modeler, create the Fluid Domain section in the Helical spring pipe.
- Now close the 'Design Modeler' tab.



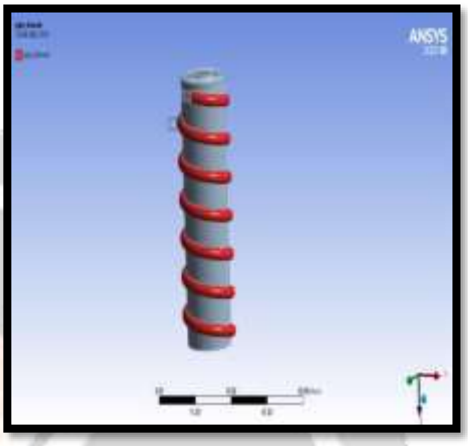


Fig - 8.1: Ansys Fluent Toolbar

Fig – 8.2: Fluid Domain of Pipe

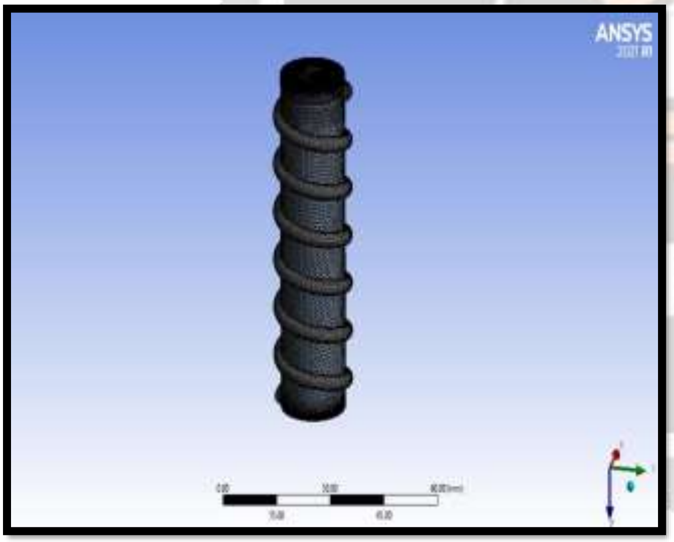


Fig - 8.3: Meshing Of 18650 Cell

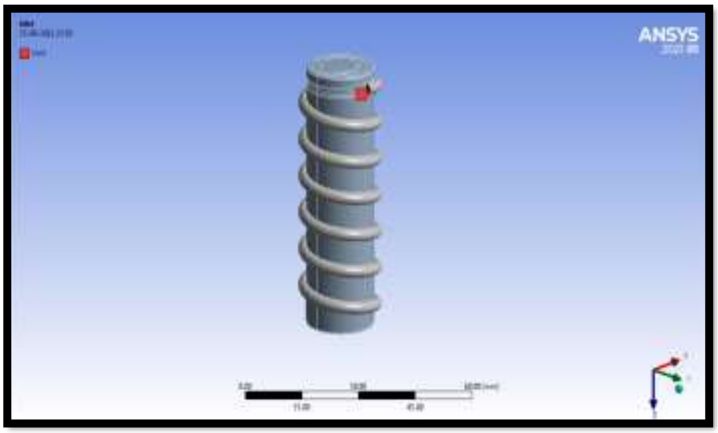


Fig - 8.4: Inlet

WHEN INLET VELOCITY = 0.1 m/s FOR PROPYLENE- GLYCOL-WATER MIXTURE

- The Pressure, Velocity, and Temperature figures are displayed below:

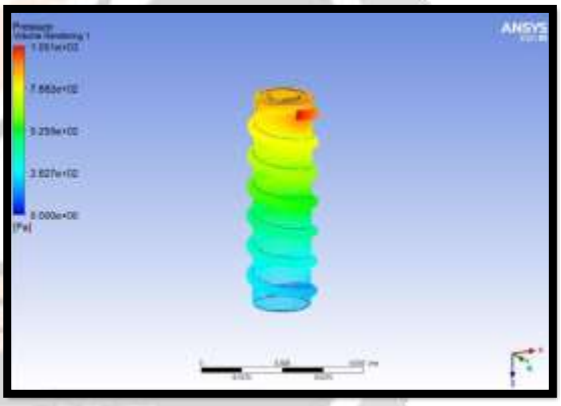


Fig – 8.1.1: Pressure

Fig – 8.1.2: Temperature

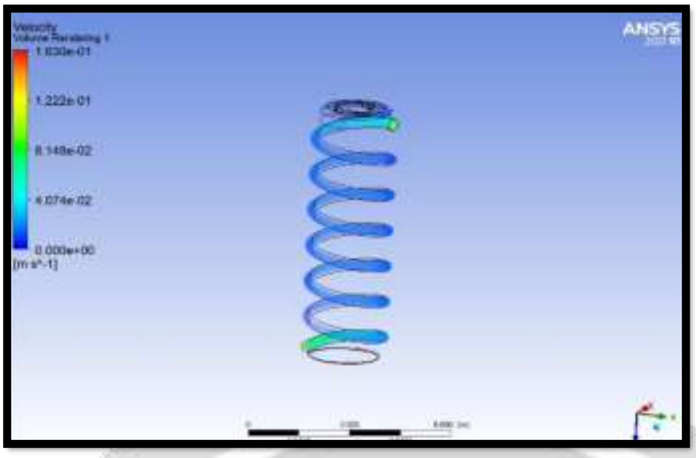


Fig – 8.1.3: Velocity

Findings and Results

The final results showed that the Propylene-Glycol-Water mixture performed better than the Ethylene-Glycol-Water mixture in reducing the battery walls temperature.

:ity 0.1 m/s	Ethylene glycol	Propylene glycol
temperature (°C)	25	25
ɛt temperature (°C)	25.37	25.338
·ry walls (°C)	43.65	41.361
sure (Pa)	411.1	1051

Table – 9.1: Comparison Table Between Two Fluids at Velocity = 0.1 m/s

:ity 0.3 m/s	Ethylene glycol	Propylene glycol
temperature (°C)	25	25
ɛt temperature (°C)	25.399	25.326

ry walls (°C)	39.544	36.791
sure (Pa)	1319	3226

Table – 9.2: Comparison Table Between Two Fluids at Velocity = 0.3 m/s

GRAPHICAL REPRESENTATION AT INLET VELOCITY = 0.1 m/s:

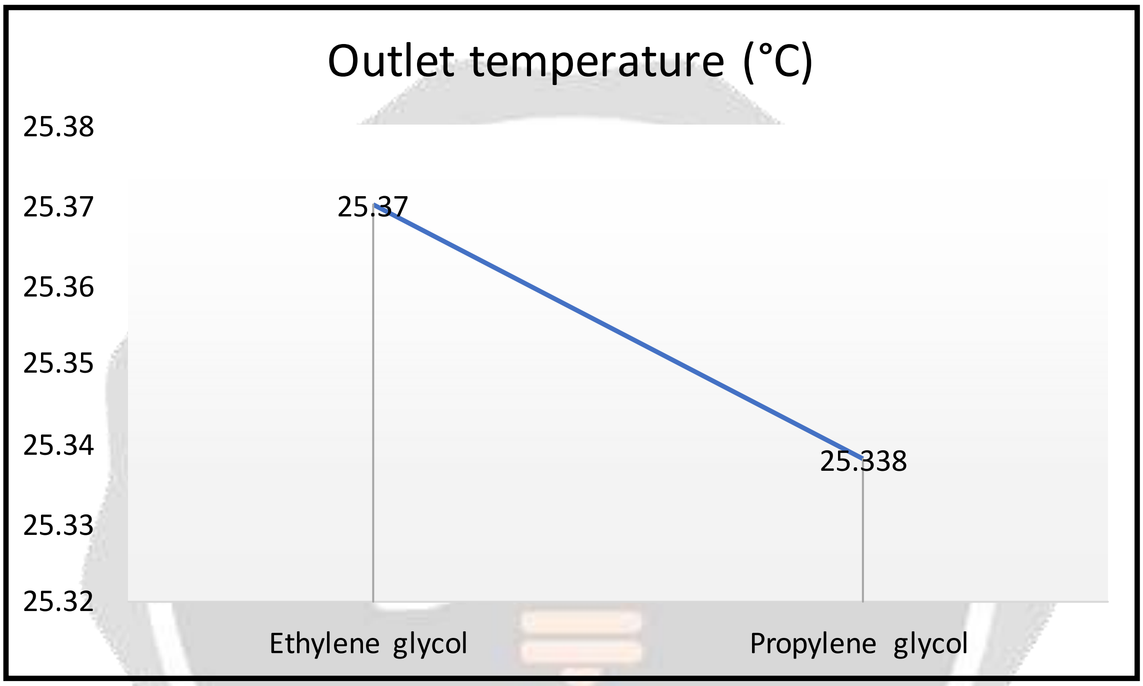


Fig – 9.1.1: Outlet Temperature

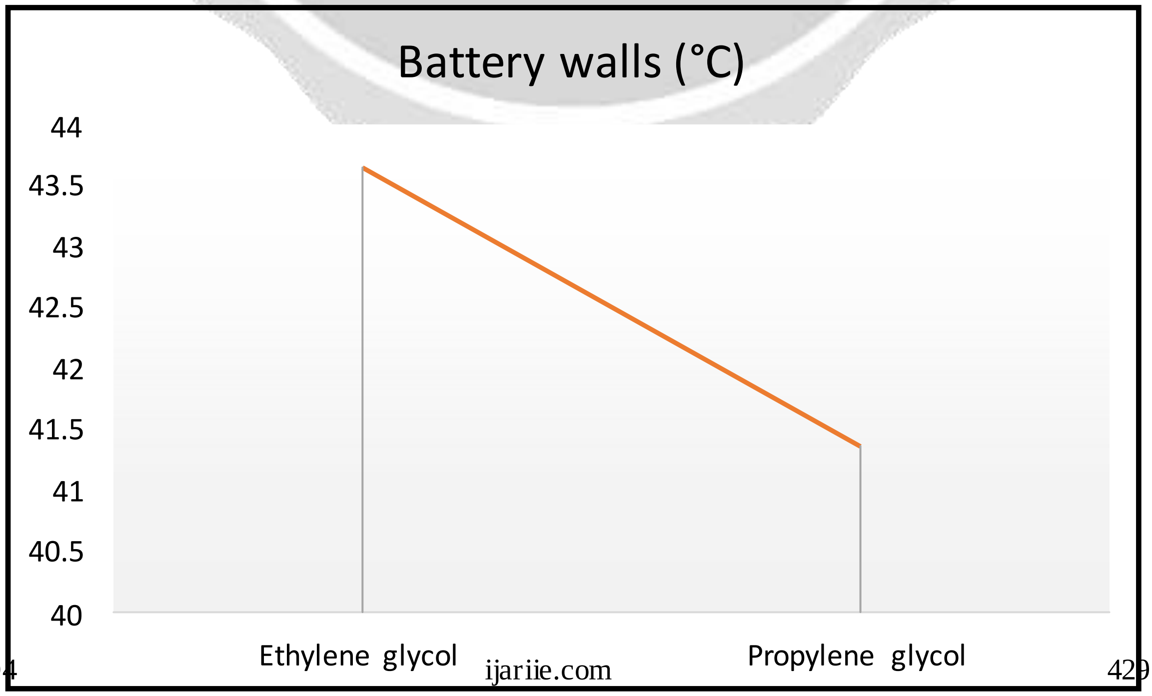


Fig – 9.1.2: Battery Walls

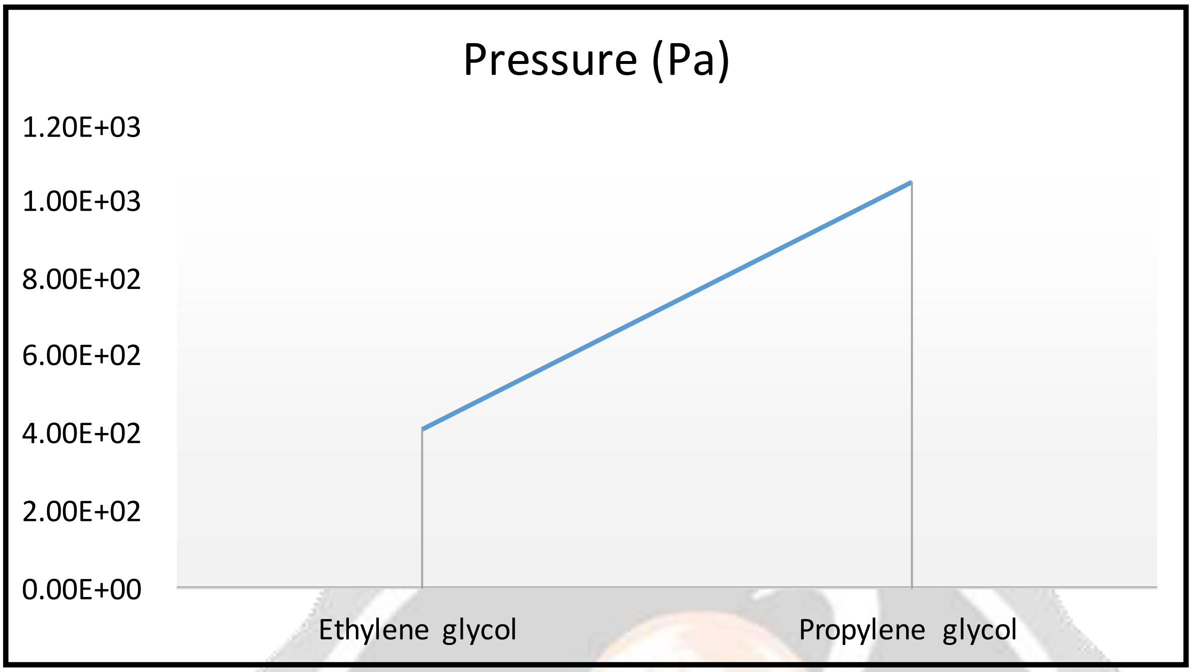


Fig – 9.1.3: Pressure

GRAPHICAL REPRESENTATION AT INLET VELOCITY = 0.3 m/s:

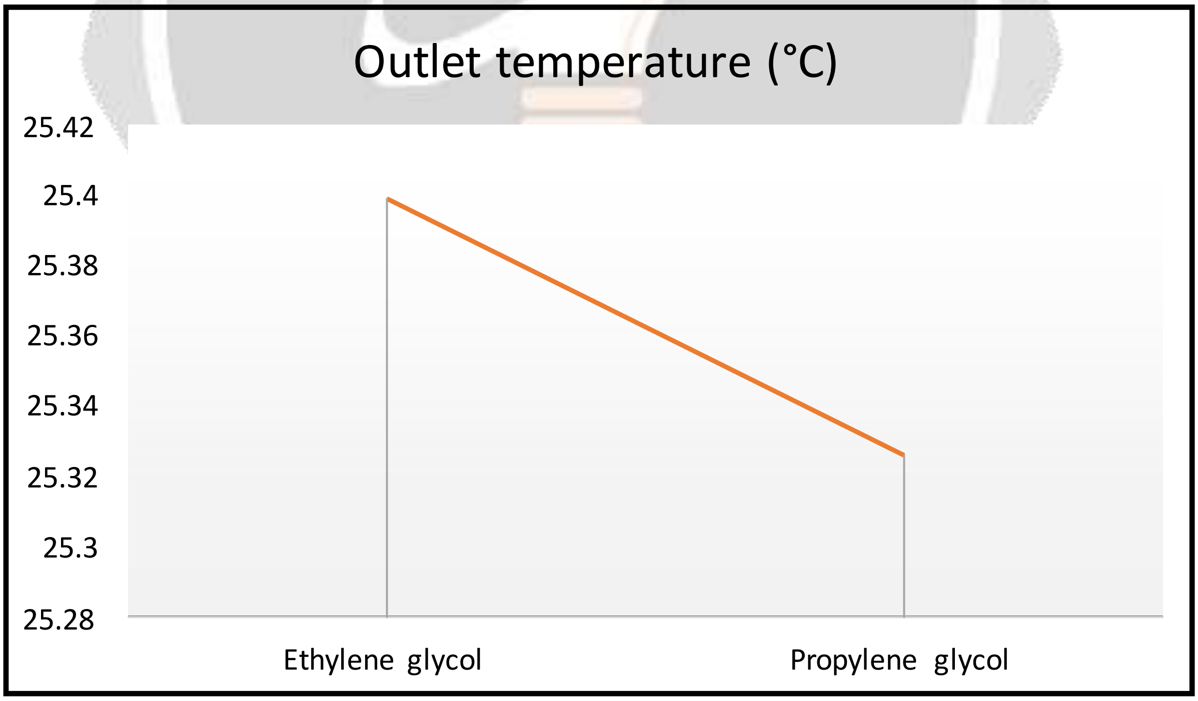


Fig – 9.2.1: Outlet Temperature

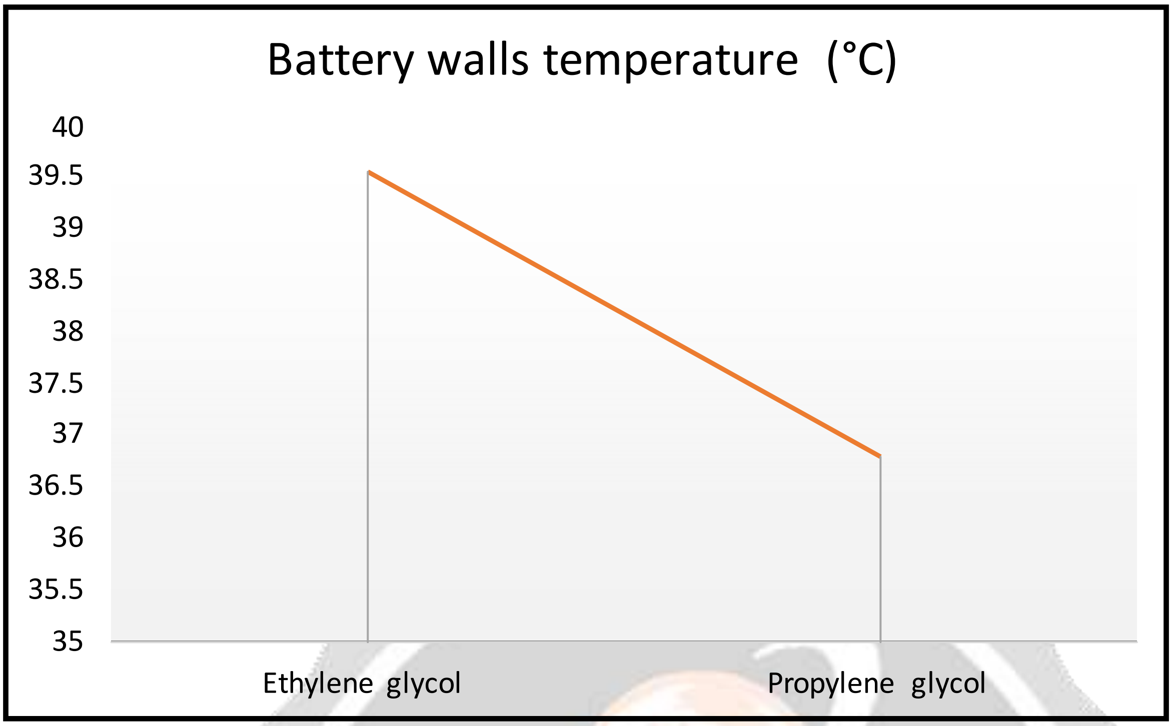


Fig – 9.2.2: Battery Walls

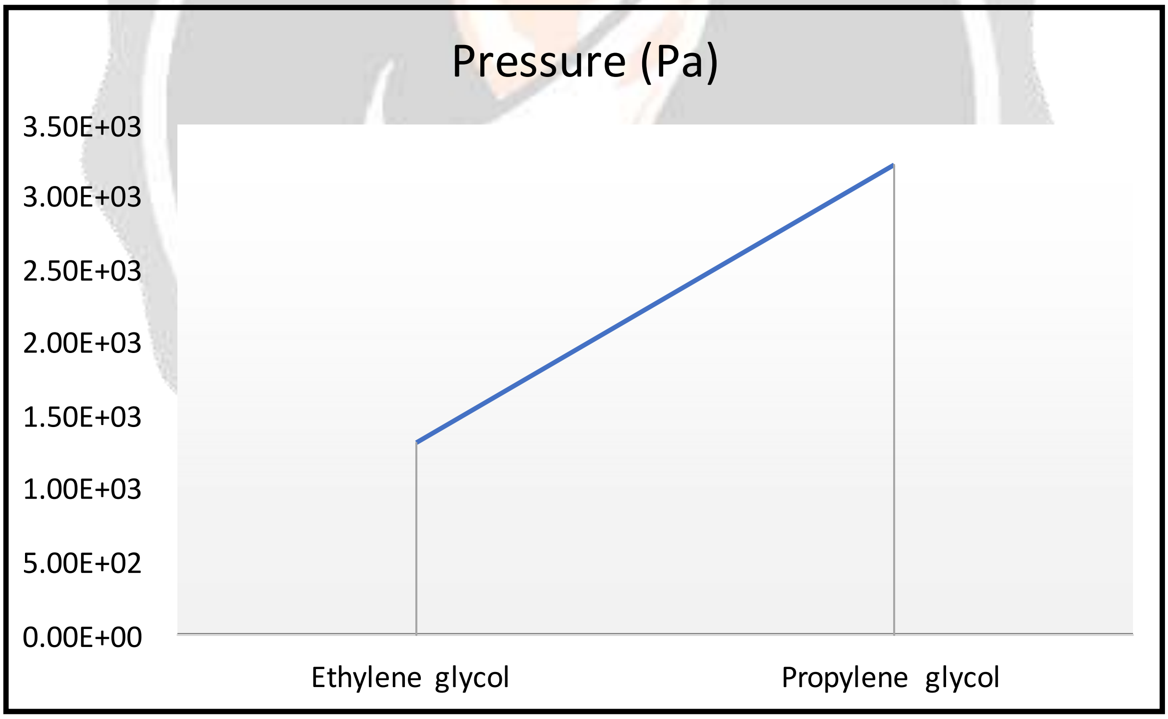


Fig – 9.2.3: Pressure

Discussion

Most of the knowledge and industrial experiences of BTMS for LIBs come from EV applications in comparison with stationary BTMS applications. There are some differences between the EV and the grid/microgrid stationary applications, mainly in requirements, such as the scale of capacity, operation voltage, and current and battery usage patterns. Therefore, the design basis and operation requirements are different, which should further be investigated.

Actively force air cooling has mostly been used for current stationary grid/microgrid connected stationary BESS applications but with limited technical information available. The gaps in basic engineering knowledge and operation experiences could be filled by internal case studies for the existing projects and close collaboration with technology suppliers. The BMW air cooling system used in Vattenfall projects could be considered as a simple air-cooling (passive cooling) solution for the stationary application in comparison with common air-cooling concepts applied for LIB TMS. Liquid cooling has widely been used in EV applications with different system configurations and cooling patterns. The BMW liquid cooling currently used in Vattenfall projects is a relative sample indirect liquid cooling solution in comparison with the liquid cooling systems in other EV applications. There is a general trend to increasing liquid cooling in stationary LIB TMS based on communications with some stationary BESS suppliers and users. The benefits may mainly be expected to reduce the footprint of BTMS and improve the lifetime and safety of LIBs. However, the benefits of stationary applications are not varied clear and under investigation.

It is difficult to give an apparent comparison between air cooling and liquid cooling for stationary applications without a fair comparison basis and specifying the applications because it is generally projected (service or application) dependence. The selection of a better BTMS is generally an optimization of important performance based on relevant KPIs, in which trade-offs should be made among many factors such as costs, complexity, cooling effects, temperature uniformity, and parasitic power consumption. Thermal modeling and simulation may be the best way to give a better comparison for different technical options if proper KPIs have been chosen together with economic factors.

According to the simulations, the BTMS depends on many factors such as cooling system type, the surrounding temperature, operation conditions, and C-rate. The advantages of using air cooling are that the system is a simple structure, low cost, easy maintenance, and the parasitic energy consumption is low during the system operation process due to the lower air viscosity. Moreover, according to the result, the air cooling keeps the cell temperature difference under the limit of 5°C event at high C-rate and surrounding temperature. However, the air cooling can keep the cell working under the optimum temperature only at low C-rate and low surrounding temperature. Furthermore, having low surrounding temperature can affect the heat generation in the cell, as shown in Figure 31, and can be further illustrated in Figure 33 with the temperature developed for the cell at different surrounding temperatures. The result of the air-cooling operation condition is presented in Table 19. Furthermore, it is also more challenging to have an evenly distributed cooling performance between the cells in the pack as air has a low viscosity that makes it flow less controllable.

Using liquid cooling for the BTMS allows the cell to operate at a higher C-rate compared to air cooling since the refrigerant R134a has higher heat capacity than air. According to Figure 35, the cell can be operated at a higher C-rate and surrounding temperature, keeping the maximum temperature under the optimum limit of 35°C. Besides, according to the literature study, the liquid cooling has other advantages over air cooling such as high heat transfer, handles large cooling loads in scenarios (high power draws, high environment temperatures), better thermal balance and uniformity temperature distribution at certain conditions. The liquid cooling system also has the advantage of occupying less space compared to the air-cooling system, but it is not so crucial for BESS, where space is not limited as for EV applications. However, BTMS using liquid cooling is more complex, requires more maintenance, has a higher cost compared to air cooling, and has potential leakage, which is a safety hazard. In addition, the maximum temperature difference in the cell is higher when using liquid cooling for the BMW pack design compared to air cooling, and this is illustrated in Figure 37. The figure shows that the ΔT max in the cell at the optimum limit of 5°C and considered this shows that the maximum C-rate must be decreased for all cases for discharge except the T32 case compare with only taken the temperature max limit of 35°C into consideration. The result is illustrated in Table 21. This is due to the pack design, which makes one side of cells (cell floor) only conducting with the cold plate, and it is harder to distribute the heat through the whole-cell due to the large size of the prismatic cell.

Even when using air cooling, indicate that the cylindrical batteries achieve better performance from air cooling, since the investigated parametric influence on a cylindrical battery module due to the battery's distribution and size compared with prismatic batteries.

Furthermore, the performance comparison between the liquid and air cooling for different surrounding temperature cases is presented in Table 22. The comparison shows that using liquid cooling, the LIBs can be operated at higher C-rate and high surrounding temperature cases, such as at T32 compared to air cooling. However, the result shows that air-cooling is better at surrounding temperatures below 18°C during discharge. This due to that using liquid cooling during discharge at surrounding temperature 18°C or below will create high ΔT in the cell, above the optimum limit of 5°C. This can be seen in Table 21 at case T12 during discharge, where the max C-rate decreased by 17%.

LIBs, after many cycles, lose their capacity, and after a certain period, the cells reach end-of-life and need to recycle. If the cells do not follow their recommended operation temperature, it will appear many thermal issues that affect the performance of the cells badly. The cell operation temperature can affect the cell performance degradation at elevated temperatures, aging effects at low temperatures, thermal runaway under uncontrolled heat generation and abuse conditions, and temperature maldistribution, mostly due to BTMS setup. Finally, there is simply no BTMS solution that would fit all applications. It should instead be thoroughly investigated and optimized based on the requirements of what the system will be used for. There are several external factors when selecting a suitable thermal management system, such as the use case, cost, safety, manufacturability, life-expectancy, and other factors.

Conclusion

In this project, the status of BTMS technology applied for stationary lithium-ion battery module was investigated. This project illustrates the most commonly used battery thermal management systems. One of the main contributions of this work is to present a thorough comparison between two fluids for a cooling method specific to 18650 lithium-ion cells based on CFD simulations and real industrial use cases. The contribution of this study is twofold. First a comparison based on the literature and market research, and second new simulation for a cooling method on a battery module have been performed. Each of the fluid used in this method has been simulated to find their limits and they are compared to one another based on the specific criteria used in the BTMS industry.

The following conclusion was drawn from this work:

- Propylene-Glycol-Water mixture gave much better results when compared to Ethylene-Glycol-Water mixture at both maximum and minimum velocity.
- At maximum velocity of 0.3 m/s Ethylene-Glycol-Water mixture was able to reduce 10.5°C of temperature in battery walls. The temperature came down to 39.5°C from 50°C.
- At maximum velocity of 0.3 m/s Propylene-Glycol-Water mixture was able to reduce 13.2°C of temperature in battery walls. The temperature came down to 36.8°C from 50°C.

All things considered, there is simply no BTMS solution that would fit all applications. it should rather be thoroughly investigated based on the requirements, using the thermal parameters namely, the temperature gradient in a cell and a module, the maximum temperature and the required coolant flow. Furthermore, there are several external factors in choosing the right thermal management solution e.g., type of industry, use case, cost, safety, manufacturability, life-expectancy, and others.

Future Scope

In this study, batteries were considered as a uniform body with constant heat generation. Even though this is a fair assumption, for a more comprehensive and case by case analysis, parameters such as the state of charge, variable resistance, and individual battery components should be included in the CFD simulation. In addition, an actual design for an electric vehicle or energy storage application needs transient simulations based on the expected driving or load cycle. For example, the driving cycle of a fully electric car is very different from a hybrid, therefore the use case should be considered in a transient CFD model.

Obviously, as with all the simulation studies, nothing is approved until it has been tested. This thesis illustrates a good foundation for comparing different cooling methods. However, there are several parameters that might affect the outcomes when testing an actual battery system e.g., leakage, improper thermal contact, turbulence, aging, thermal runaway, and so forth.

The work conducted in this thesis can be improved in several aspects. Aging factor needs to be implemented in the model. This can make the model capable of simulating and study cell capacity degradation under cells' lifetime. A more accurate study of the operational cell condition can be conducted. Furthermore, the CFD model has been developed for the cell. However, the model requires more parameters and needs more time for the BTMS system, and therefore it's not mentioned in this thesis. With the CFD model, the heat flow in the pack can be studied more in detail.

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