

Comparative Study of Electric Vehicle Battery Cooling System Using Liquid Flow-Channel

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Abstract - Battery thermal management has been a very active research focus in recent years because of its great essentiality for electric vehicles. The proposed cooling system utilizes a liquid coolant that circulates through channels embedded within or adjacent to the battery cells, effectively absorbing and dissipating heat generated during operation. By maintaining the battery temperature within an optimal range, the liquid cooling system enhances the efficiency and lifespan of the battery while preventing thermal runaway, which can lead to sudden failures. Simulation results show that three cooling channels were utilized to compute the rate of heat transfer for water as well as ethylene glycol. In the serpentine channel, the heat transfer rate of water is high at 39.12% as compared to ethylene glycol also in the wavy cooling channel, the heat transfer rate of water is high at 31.35% and in the cells embedded channel, the heat transfer rate of water is 5.09%, from the further research work serpentine channel is efficient because of the heat transfer rate is high and water is more efficient as a working fluid. Electric vehicles utilize lithium-ion batteries, and proper thermal management ensures optimal performance, safety, and lifetime.

Keywords - lithium-ion batteries, Rate of heat transfer, Liquid cooling, Electric vehicle.

I. INTRODUCTION

Electric vehicles have rapidly progressed in recent years with the developments of battery technology. Such batteries are now designed to drive longer distances, charge much faster, and overall work better. But with such developments, there arises a new challenge to effective thermal management. The most common energy storage solution found in electric vehicles is Lithium-ion, which is highly sensitive to temperature variations. In-service operating conditions, with high loadings and fast charging particularly, promote excessive heat generation that will degrade battery performance, shorten its lifespan, and under extreme conditions raise safety issues, such as thermal runaway. Traditional methods of cooling used to manage the

temperatures of a battery, including air cooling, tend to fall short when trying to achieve the kind of thermal stability required, especially in high-performance applications [1]. The consequence was that the liquid cooling systems were far more efficient and reliable alternatives to air-cooled versions. It describes the typical components of a liquid cooling system: the coolant, cooling channels, heat exchangers, and pumps, and discusses how these elements work together to regulate temperature. This has led to the enhancement of the performance and lifespan of EV batteries by keeping them within a narrow temperature range and making electric vehicles safer and more reliable. Ming Chian Yew et al. discuss the design, operation, and optimization of liquid cooling systems and will be able to shed some light on their future in electric mobility. Efficient thermal management is one of the most important aspects of electric vehicle (EV) technology, especially regarding battery systems. The performance, lifespan, and safety of EV batteries are highly dependent on maintaining optimal temperature ranges during operation and charging [2]. Lithium-ion batteries, widely used in EVs, have high energy density, generating a lot of heat, especially when current loads are high or under rapid charging conditions. A cooling system for a battery is designed to maintain a uniform temperature of the battery pack, hence avoiding thermal runaway, and most such systems have been integrated with advanced thermal control techniques, such as liquid cooling, air cooling, or phase-change materials. Future innovations in thermal management could, therefore, lead to increased system reliability, better energy efficiency, and potentially high energy densities in newly designed battery forms.

II. LITERATURE REVIEW

Eswaramoorthy et al. [3] have drawn attention to electrode modification and nanofluids in cooling systems as a technique for improving thermal

performance. This review discusses how electrode size and material modifications may enhance conductivity and, hence, thermal performance. Reducing electrode sizes significantly improves efficiency, but the manufacturing challenge is enormous. Saksham Kaushik et al. [4] have researched many cooling systems and designed a heat pipe to extract heat from electrical batteries. Their research vividly explains how liquid cooling with different coolants can significantly improve the efficiency of battery cooling. Rao et al. [5] highlight the vast importance of proper temperature controls in systems while ensuring that effective design is essential for keeping up with prolongation and fitness in batteries too. Further with growing strength and rapidly escalating rate, the safety issues develop more inside. With various applications demanding either high values or fast ones along with acceptable performance developments quite a few BTSMs emerged to be actively categorized within active or passive varieties. Lin-Yang Li et al. [6] emphasize structural elements more. They explain a low-complexity heat generation model of a single battery cell and a specific cooling model in which significant performance may be gained by combining liquid cooling with thermoelectric cooling. Besides, Jiang et al. [7] reported a simulation model of different C-rates, liquid flow rates, contact areas between batteries, and interfacings with cooling channels concerning the thermal behavior and response of the battery packs. Their work of research exemplifies a sense of thermal behavior at the charge/discharge cycle operation and the recent advancement in the technology of the battery, such as material, design, cooling, etc., for effective thermal management and hence their efficiency. Wudi Dai et al. [8] have discussed the need for liquid cooling as a primary method of battery thermal management in electric vehicles. Their work is on the improvement of heat transfer capabilities where they numerically analyze various cooling plate channel cross-sections under high-current discharges of prismatic battery modules. They introduced the j/f factor that considers flow resistance and heat transfer capacity to evaluate cooling plates and analyzed pressure and velocity distributions to improve coolant flow schemes. Jiateng Zhao et al. [9] introduce a new cooling concept of cylindrical batteries by using mini-channel liquid cooling. In the paper, the authors carried out a numerical study concerning the heat dissipation performance with varying numbers of channels, mass flow rates, direction, and size of the

inlet. The authors can show that the maximum temperature of cylindrical batteries can be kept below 40 degrees Celsius under conditions of four or more mini-channels and sufficient mass flow rates. Yang et al. [10] describe a series ventilation system in which the air flows into a duct over the surface of the battery, increasing in temperature along its path. However, this method tends to reduce the temperature difference between the air and the battery, and hence there will be variations in the temperature of cells in the pack. The flow rate is higher with lower temperatures for the upstream cell close to the air inlet. Pandya et al. [11] point out the need for efficient thermal management of lithium-ion battery systems in maintaining performance and safety since overheating causes degradation and a drop in efficiency. Liquid cooling systems are known for their better heat dissipation properties that help to keep the desired temperature within a battery and the system as well. The use of microchannels in liquid cooling configurations further enhances the heat transfer capabilities and promotes uniform temperature distributions within a battery pack. Y. Lai et al. [12] have reviewed different BTM technologies discussing the merits and demerits of each one. The authors highlighted that liquid cooling provides the highest possible efficiency in heat transfer with very low power consumption. A review indicates that the previous literature has not focused on the compactness and weight of battery packs in EVs for liquid-cooled BTM systems. Although most of the current literature is focused on thermal performance, lightweight design has received little attention. The authors of this paper propose a new lightweight liquid-cooled BTM that would improve the cooling performance while reducing the weight, thus potentially improving the overall efficiency and range of an EV. Teng et al. [13] discussed thermal management systems applied to lithium-ion batteries, particularly in PHEVs. The authors compared different cooling modalities, specifically direct versus indirect liquid cooling configurations, by examining compactness and design complexity. Their study also compared cold plates in direct liquid cooling against indirect methods to evaluate the effectiveness of each system in managing heat generation from battery cells. Seo, Jae-Hyeong et al. [14] state that for lithium-ion batteries, especially in electric vehicles, efficient thermal management systems are necessary. They further discuss the increasing demand for battery energy density and the importance of proper operating temperatures

between 20-40 °C for reliability and performance. Air- and water-cooling methods are the most commonly used cooling techniques today. The technique of air cooling is simple but not very effective because of low thermal conductivity. Water cooling gives better capacity but with some risks of leakage and also design complications. Garud et al. [15] discussed the recent developments in battery thermal management for electric vehicles and highlighted the direct liquid cooling and PCM cooling approaches. They underpin the limitation of air and indirect liquid cooling systems and summarize key findings in the research work conducted during the last five years. The review would aim at a holistic understanding of direct liquid cooling as an approach toward the high-power density battery thermal management system. Sarchami et al. [16] have discussed the latest progress of BTMS for LIBs, and proper thermal management is crucial for efficient and safe performance. They are focusing on novel cooling designs such as modular active cooling and micro-channel liquid cooling, aiming at improving thermal efficiency, as well as reducing the temperature non-uniformity. However, it mentions that further research on the geometrical properties may enhance the overall efficiency of liquid-cooled BTMS for LIBs. Chakib Alaoui et al. [17] give an overview of thermal behavior by discussing LiFePO₄ batteries about both production and absorption of heat while the battery is being either charged or discharged. This review further explains why one ought to understand thermodynamic relations; for instance, changes within Gibbs free energy, enthalpy, and entropy. The authors further introduce how proposed BTMSs are tested in laboratory and real road settings for electric vehicles having different discharge currents. Zhang et al. [18] classify conventional heat management techniques into air, liquid, and PCM-based. Air cooling is simple. Although it has efficiency issues concerning high power dissipation related to electric vehicles (EVs) applications. Liquid cooling is more efficient. However, it caused significant temperature gradients across modules. Only PCM-based cooling could maintain uniformity of temperature. However, it has been found that there are difficulties with continuous high discharge rates. Recently, studies have shown that hybrid systems that include PCM and liquid coolant can achieve better thermal performance. Gavin White et al. [19] emphasize that efficient thermal management is key to improving battery performance, safety, and

lifespan in applications like electric vehicles (EVs). The paper categorizes different cooling methods - air cooling, indirect liquid cooling, and direct immersion cooling - and finds that direct immersion cooling has significant promise because it can raise heat transfer rates by as much as 10,000 times that of air cooling. They discuss some of the suitable dielectric fluids for immersion cooling including hydrofluoroethers, mineral oils, esters, and so on as well as some of the challenges associated with fluid cost, stability, and compatibility with battery materials. The paper also indicates deficiencies in the existing studies about long-term impacts related to immersion cooling on a battery's lifetime and security, which presents motivation to explore further research that could make these systems for industrial application. It is generally considered a significant resource for scientists and engineers designing newer EVs in developing the future generation of LIBs with improved thermal management. Chen, Z. et al. [20] use response surface methodology for optimizing various parameters, including coolant temperature, volume fraction, and start-up time of active cooling, and thus propose three optimization schemes wherein driving power consumption will be reduced by up to 35% to 40%. The key is to understand that tuning thermal management strategies according to specific discharge conditions goes a long way, and it has well-balanced active and passive cooling methods to upgrade BTMS operational efficiency for electric vehicles. Liu, Z et al. [21] A hybrid cooling system for lithium-ion battery packs based on phase change materials in combination with liquid cooling that targets thermal conditions during high discharge rates and prolonged operating cycles at elevated ambient temperatures. Numerical simulations are used to study the effects of composite PCMs, fin arrangements, and cooling water inflow schemes on heat dissipation performance. In comparison with traditional liquid cooling, the optimal performance is obtained by using composite PCMs with 12-16% expanded graphite.

Earlier research work points towards the critical aspect of thermal management systems in ensuring optimized performance, safety, and lifespan for lithium-ion batteries, particularly in electric vehicles. Direct liquid cooling is the most effective since it has shown a high ability to transfer heat away from the battery pack. The challenges include added weight, cost, and even long-term effects on battery degradation. The main objective of our research

work in electric vehicle battery cooling systems is to maintain optimal operating temperatures, improve battery efficiency and lifespan, ensure consistent performance under varying conditions, and decrease the risk of thermal runaway and battery fires.

III. METHODOLOGY

Battery Liquid cooling through channels involves circulating a coolant fluid as water and ethylene glycol as the working fluid passes through channels embedded within or around the battery cells. This

fluid absorbs heat from the battery, preventing it from reaching high temperatures. The heated fluid is then transferred to a heat exchanger radiator or chiller, where it releases its heat to the environment. Liquid channel cooling is used in electric vehicles to ensure optimal battery performance, and safety, and to extend the life of the battery. Designed various types of schemes for liquid channel cooling within battery cells. Lithium-ion cells are used and the fluid channel is made up of aluminum-cell parameters like voltage and ampere - 3.7v and 2200mah it is made up of nickel.

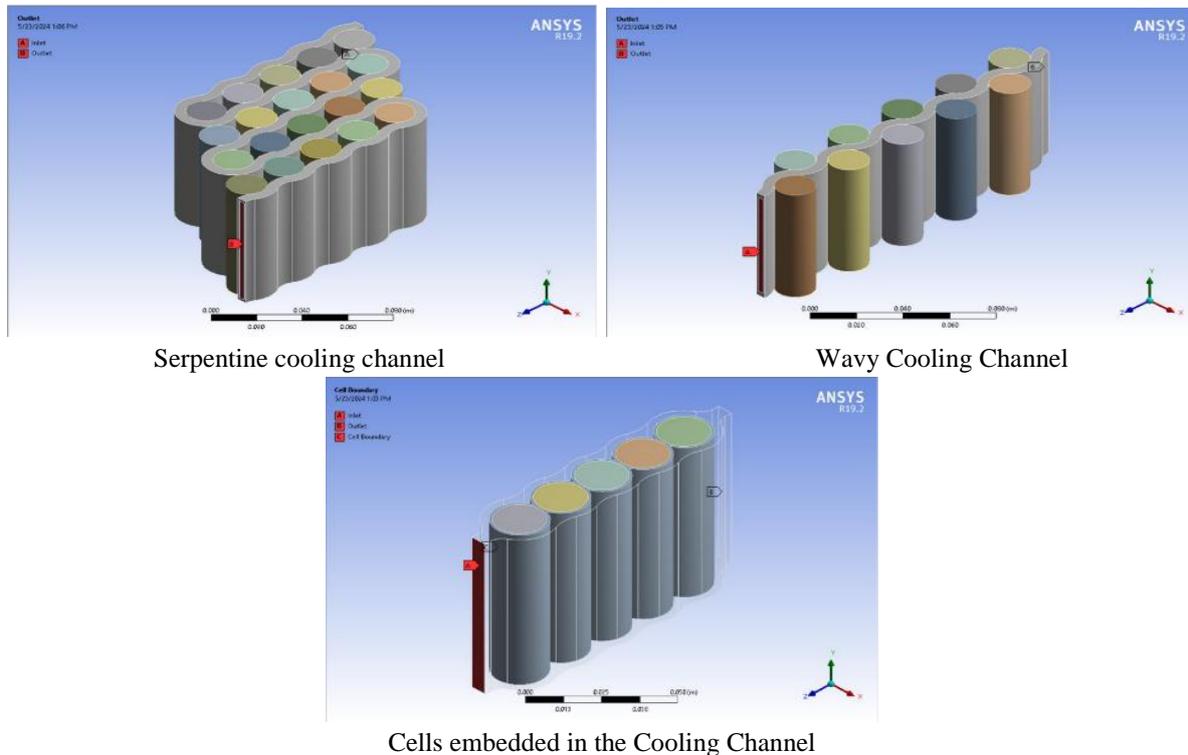


Fig 3.1 Comparative Analysis of Serpentine Cooling Channel Configurations for Cylindrical Battery Cells.

Fig 3.1 illustrates three different configurations of battery thermal management systems modeled in ANSYS, showcasing variations in cooling channel designs to optimize thermal performance. The serpentine cooling channel employs a densely packed configuration of cylindrical battery cells with an integrated serpentine cooling channel to maximize surface contact and achieve uniform heat dissipation. The wavy cooling channel features a linear arrangement with a single cooling channel along the outer periphery, prioritizing design simplicity but potentially leading to non-uniform temperature distribution, as inner cells may receive less effective cooling. Cells embedded in the cooling channel utilize a staggered layout of cylindrical cells with interspersed cooling channels, enhancing coolant flow distribution and thermal uniformity

while balancing spatial constraints. These configurations represent trade-offs in design complexity, cooling efficiency, and thermal uniformity, emphasizing the importance of selecting the optimal design based on system-specific requirements.

Water is the most common working fluid in cooling due to its high thermal conductivity that leads to effective heat transfer. It is non-toxic, environmentally friendly and rather innocuous, which makes it convenient to use. Water however needs additives or inhibitors to avoid corrosion in metallic cooling systems. It is good for moderate pressure and the density is high to enhance the convective heat transfer in liquid cooling systems. On the other hand, ethylene glycol has very good

thermal stability that enables it to work over a large range of temperatures. It has corrosion inhibitors that stop the corrosion of metal parts in the cooling system and has a low freezing point for use in cold conditions. Its thermal conductivity is better than water but not as good as water in a controlled environment. In addition, ethylene glycol has lubricating properties that protect pumps and other moving parts of the cooling system.

IV. RESULTS AND DISCUSSION

The liquid cooling system for electric vehicle battery thermal management shows that in terms of heat

dissipation and temperature uniformity, the cooling performance is considerably better than in air cooling systems. Simulation results show that the battery temperatures are maintained within the range of optimal operating temperatures during high-load and fast charging conditions, which are usually between 25°C and 40°C. The heat transfer rate of the working fluid is calculated in Eq. (1),

$$Q = \dot{m} * Cp(T1 - T2) \tag{1}$$

Q (kW) is the heat rejected from the cell,

m (kg) of the working fluid,

Cp (kJ/kg k) is the specific heat capacities of fluids,

T1 (K) is the outlet temperature,

T2 (K) is the inlet temperature of cooling channels.

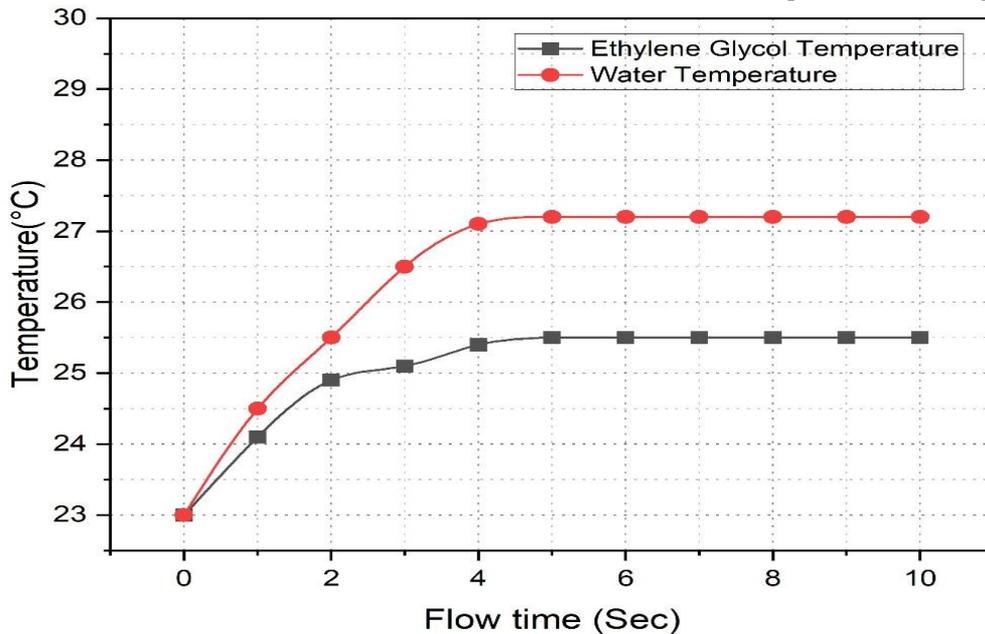


Fig 4.1 Temperature Variation of Water and Ethylene Glycol in Serpentine Cooling Channel

Figure 4.1 shows a serpentine liquid cooling channel containing ethylene glycol and water simulated in this graph. In the flow time, the temperatures of the fluid, where heating occurs, rise first as their temperatures stabilize after around six sec of flow time. From every moment, ethylene glycol always retains slightly higher temperatures compared with that of water because of such diverse thermal properties as heat capacity and thermal conductivity. This stabilization suggests that the serpentine channel is good for heat dissipation and thermal equilibrium. This makes it suitable for high-end cooling applications.

In the serpentine channel liquid cooling simulation, the flow rates of water and ethylene glycol are each set at 1 kg/s. The inlet and outlet temperatures for water are respectively 301 K and 296 K, and the inlet and outlet temperatures of ethylene glycol were 299 K and 296 K. Using specific heat capacities of 4.18 kJ/ (kg K) for water and 2.43 kJ/ (kg K) for ethylene glycol in the calculations, the generated heat rejection comes out to be 20.9 kW for water and 7.29 kW for ethylene glycol from Eq (1). It means significant cooling efficiency of the system by using these fluids

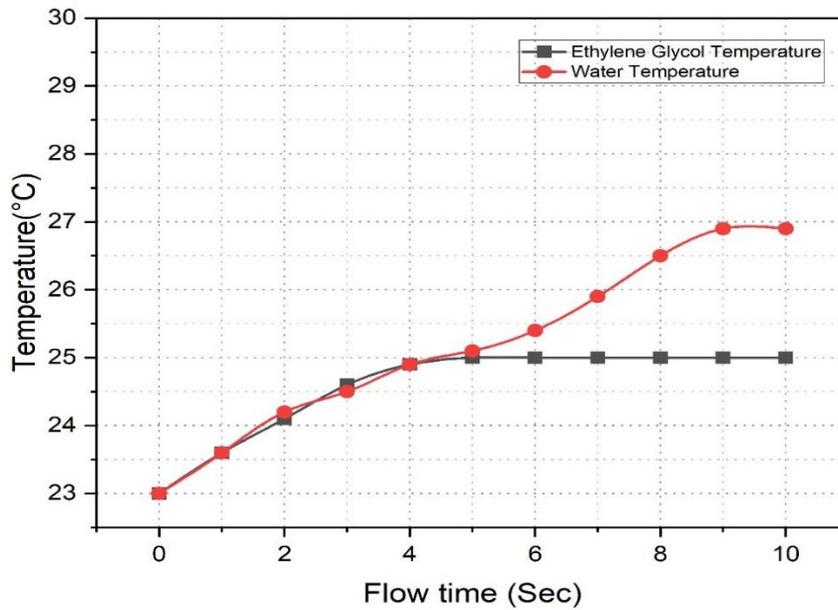


Fig 4.2 Temperature Variation of Water and Ethylene Glycol in Wavy Cooling Channel

Figure 4.2 shows the variation of water and ethylene glycol temperatures over the simulating flow time in a wavy cooling channel. Water increases continuously in temperature, which means that water takes up heat since it is used as the primary coolant. On the other hand, ethylene glycol has a nearly steady temperature pattern after an initial increase, which suggests lesser rates of heat transfer or greater thermal stability in the same conditions. This behavior indicates the unique thermo-physics of the two fluids, particularly specific heat capacity and thermal conductivity, and how these affect cooling performance within a wavy channel configuration. Wavy cooling channel simulation compares the

thermal performance of water and ethylene glycol under the same conditions. For water, the mass flow rate is 1 kg/s with an inlet temperature of 300 K and outlet temperature of 296 K. Specific heat capacity of water is 4.187 kJ/kg K, and the heat transfer rate is calculated as 16.748 kW. Ethylene glycol, so the heat transfer rate in this case is about 4.7 kW from Eq (1). Temperature profiles over the time of flow indicate that the capability of heat transfer through water is higher because the specific heat capacity of the material is greater, thus ideal for thermal management cooling in applications rather than ethylene glycol.

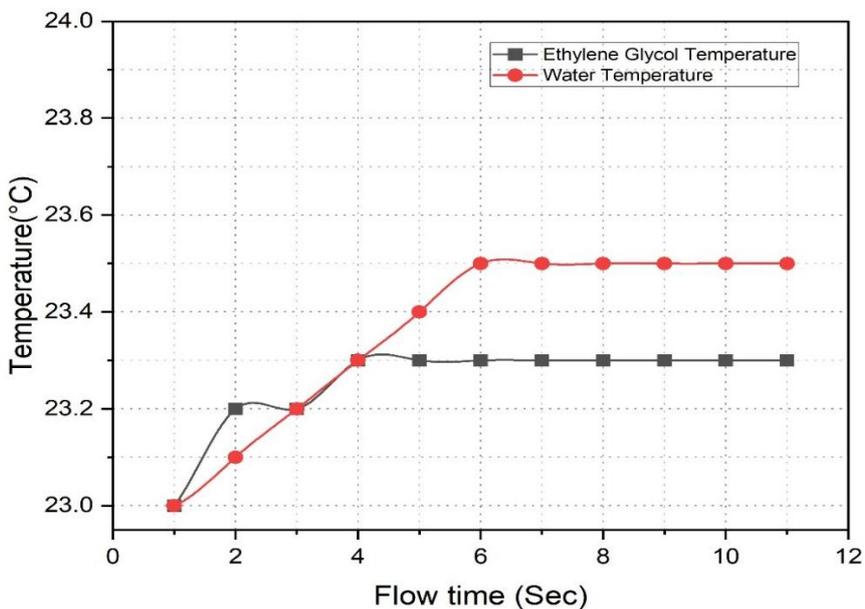


Fig 4.3 Temperature Variation of Water and Ethylene Glycol in Cells Embedded in the Cooling Channel

Figure 4.3 show depicts the temperature profiles of the coolant fluids water and ethylene glycol over the flow time in a cells embedded cooling channel. The water indicates an initial sharp temperature increase, stabilizing to about 23.5°C at the sixth time step, meaning that the heat is being dissipated effectively and that steady-state conditions have been reached. The other one, ethylene glycol, shows a slower temperature rise and stabilizes at a lower maximum temperature of about 23.3°C. It is also due to the lower thermal conductivity and specific heat capacity of ethylene glycol compared to water. The simulation compares the performance of water and ethylene glycol as coolant fluids under identical flow conditions with a mass flow rate of 1 kg/s. For water, the inlet temperature is 296.65 K, outlet temperature 296 K, and specific heat 4.187 kJ/kg K, whose heat transfer rate is equal to 2.721 kW. In the case of ethylene glycol, the heat transfer rate is 1.062 kW from Eq (1). Temperature profiles of water overflow time prove that because of better heat transfer capability, water has significantly better thermal management than ethylene glycol inside the cooling channel.

Table no 1 – Heat rejected from water and ethylene glycol

Channels	Water (%)	Ethylene Glycol (%)
Serpentine	39.12	13.65
Wavy	31.35	8.80
Cells Embedded	5.09	1.99

Table 1 presents the values of heat rejection for water and ethylene glycol through three channels. The Serpentine Channel showed the highest heat rejection rates representing 39.12% for water and 13.65% for ethylene glycol. Cells embedded in the cooling channel have the lowest contributing 5.09% for water and 1.99% for ethylene glycol of the total heat rejection, which shows a progressive reduction in the amount of heat across the cooling channels.

V. CONCLUSION

- Liquid cooling systems for electric vehicle (EV) batteries are an efficient and reliable means of thermal management, ensuring optimal performance and long life of the battery. Liquid cooling systems have higher thermal conductivity and heat transfer capabilities than air cooling.
- This will enhance the safety of the battery, extend the operational life, and improve energy

efficiency, making liquid cooling a vital solution for modern EVs.

- Analysing the temperature and heat transfer rate of the serpentine channel of water is 39.12% and ethylene glycol is 13.65%, in the wavy channel Q of water is 31.35% and ethylene glycol is 8.80% and, in the cells, embedded channel the Q of water is 5.09% and for ethylene glycol is 1.99%.
- It concludes that the serpentine channel is more efficient because the surface contact area of the cell is higher the heat transfer rate is high as compared to other channels and water is more efficient as a working fluid.

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