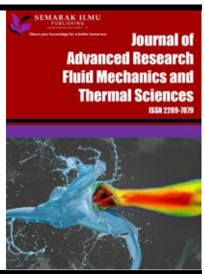
SEMARAK ILMU PUBLISHING

Journal of Advanced Research in Fluid Mechanics and Thermal Sciences

Journal homepage:
https://semarakilmu.com.my/journals/index.php/fluid_mechanics_thermal_sciences/index
ISSN: 2289-7879



Improving Li-ion Battery Performance with Internal Cooling

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ARTICLE INFO

Article history:
Received 18 August 2024
Received in revised form 20 November 2024
Accepted 27 November 2024
Available online 10 November 2024

Keywords:
Internal cooling; battery thermal management system; li ion battery; rectangular flow channel; de-ionized water

ABSTRACT

The use of Li-ion batteries has expanded fast in recent decades due to the rising use of electric vehicles, mobiles, laptop, robots' drone, digital cameras etc., but there are numerous issues with batteries, including thermal runaway, cell rupture, decreased battery life, and an internal short circuit caused by overheating and overcharging. High-power draw systems tend to heat the battery beyond its safe operating temperature range, reducing the cell's lifespan. Researchers used a variety of battery heat management systems (internal/external) to tackle these issues. Most researchers, as well as commercial applications, have embraced external cooling systems employing air, PCM, or liquid cooling. There is a shortage of study on cell internal cooling. Internal cooling of Li-Ion prismatic cells and battery packs has been designed and analysed in this study (2S-2P). Under various C rates, we observed heat generation. Then we used rectangular flow channels inside the electrodes and de-ionized water as a coolant. CFD analysis were done for simulation. Without cooling, the maximum temperature of the battery pack was 338K, but after internal cooling, the maximum temperature of the battery pack was 306K, which is ideal for maintaining good battery health.

1. Introduction

The battery is a type of electrical energy storage device made up of many electrical-chemistry cells with external circuitry connections that are often used to power equipment such as electric vehicles, drones, mobile phones, and digital cameras. Mobile phones, digital cameras, robotics, and other such devices are examples. Primary and secondary cells are the two major types of cells.

A main cell is a type of battery that is not rechargeable or reusable. It's commonly found in lights, cameras, toys, watches, radios, clocks, and other small home items. Secondary batteries can be recharged. This method of charging and draining will be repeated several times, depending on the type of battery utilised. The cell receives electrical energy in order to charge it. They're commonly used in Hybrid Electric Vehicles, laptops, smartphones, fitness bands, drones, and robotics, among other things.

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https://doi.org/10.37934/arfmts.125.1.220233

In this developing Era and modern-day electronics, the Li-ion rechargeable battery is the most advantageous equipment to utilise. Lithium-ion batteries have a higher stability and can be recharged hundreds of times. During operation, internal resistance causes heat to build up inside Li-ion cells. The intrinsic characteristic will have an impact on the battery's performance. To fulfil the high-power demands of electric and hybrid electric cars, Li-ion packs must be connected in series and parallel, resulting in dramatic temperature spikes and substantial pack performance loss. To summaries, we must create a thermal management system that will allow us to transport generated heat out of the battery while maintaining cell performance within the required temperature range.

Both internal and external cooling methods were used to cool the Li-ion cell. Coolants like water and liquid electrolyte have been used for both exterior and internal cooling. Internal Li-ion battery colling is one of the most important strategies in a thermal management system because it allows for faster colling by reducing thermal resistance.

Li-ion batteries are sensitive to temperature and voltage. The safe temperature range is between 10 and 55 degrees Celsius. In a lithium-ion battery, the electrolyte, which is flammable at its core, is the most dangerous component. The exo-thermic reaction rate inside the battery increases when the battery temperature climbs above 80°C. When the voltages of lithium-ion batteries reach the permissible ranges of 2.5 to 3.65/4.1/4.2 or 4.35V, they are strained (depending on the chemistry of the cell). Excessing this voltage range causes premature ageing and safety hazards due to the reactive components within the cells. When a battery is kept for an extended period of time, the safety circuitry's low current consumption can lead the battery to drain below its shutdown voltage. The battery's (or charger's) failure by the battery management system may make frequent charging is very common. Because to lithium plating, many types of lithium-ion cells cannot be charged safely below 0°C, which can cause difficulties such as internal short-circuit routes.

Internal short circuits can occur as a result of rough handling and overcharging. The battery expands as it fills up with lithium ions. Too much lithium can impair the battery's mechanical integrity as well as its internal insulation. Overcharging can cause electron-conducting metallic deposits between the electrodes in some situations. Temperatures between 20 °C and 35 °C are ideal for charging the battery. Li-ion batteries that have been overcharged or overheated might have catastrophic consequences such as thermal runaway and cell rupture. The cathode materials degrade as a result of overcharging, causing the electrolyte to oxidise. Both cooling and heating can be affected by changing temperatures in the battery or outdoors in our surroundings. To maintain an optimal temperature, various types of thermal management systems are used. Controlling the temperature reduces the chance of moisture collecting inside the battery and prevents the electrical equipment from overheating or freezing.

The BTMS is required to control the thermal behaviour of the battery. Its main goal is to keep the battery's temperature as low as possible. Performance, weight, size, cost, dependability, safety, and energy consumption are all factors considered when building these systems. Water and liquid electrolyte have been used as coolants inside the internal thermal management system to mimic and copy batteries and reduce heat. The thermal resistance of the heat source to the cooling fluid is reduced. Convective heat is transferred to a liquid vapour phase change fluid with a high heat transfer coefficient, resulting in a small temperature rise in the cells.

In the battery thermal management system, heat is evacuated from the battery. Researchers discovered three important concerns with the BTMS that should be addressed in order for the battery to be more efficient:

i. Thermal Runaway — Temperature and voltage are two elements that cause lithium-ion batteries' conductivity to deteriorate. Temperatures of 10 to 55 degrees Celsius are regarded as safe (can be varied). The electrolyte, which is flammable, is the most serious threat in a battery. As the battery temperature rises over 80°C, the heat-releasing response rate inside the battery accelerates.

ii. Voltage Limits – The voltage range of lithium-ion batteries is 2 to 5V. Excessive voltage series speeds up the rate of discharge and needs a high level of protection. The sensitive components within the cells can draw fewer current charges with time.

iii. Internal Short Circuits (internal short circuits) - Overcharging and improper battery management are to blame. As the battery expands, excess lithium is created, causing lithium ionisation and mechanical stress within the battery, jeopardising the insurance. Overcharged batteries generate metallic deposits near the electrodes, which might cause problems. Problems with charging - The battery's optimal charge temperature should be kept between 20°C and 35°C (which can be modified). Overheating or overcharging can result in a range of issues, including thermal runaway and cell structure and component damage. Overcharging can cause the cathode materials in the cathode section to decompose, resulting in electrolyte oxidationcausing the battery to drop below its endpoint voltage.

All above three are responsible for reducing battery life. Table 1 shows reason for low battery life and remedies provides researchers.

There are several ways that can be employed to address above problems. Active cooling methods such as liquid type (immersion cooling), PCM-based cooling, air-cooled convection, and passive cooling methods such as natural air convection cooling are also available and in use. Internal cooling techniques, such as colling within the electrodes, are relatively unusual. Internal cooling, when compared to external cooling, reduced overall temperature and increased cell temperature uniformity by up to 5 times, according to a study of multiple BTMs systems produced by researchers. However, due to fabrication difficulties, only a small amount of work has been completed. For various discharge rates and cooling methods, Mohammadian *et al.,* [13] investigated the highest limiting temperature within the battery versus the level of charge. When the discharge rate increases while the state of charge drops, the temperature inside the battery rises. Internal cooling reduces the maximum temperature within the battery by up to 303 degrees Fahrenheit. External cooling is definitely insufficient to keep the battery cells operating at their best, as it lowers the battery's highest limitation temperature to 314K. The recommended temperature range for maximum power capability and tolerable thermal ageing is between 20°C and 40°C. Internal cooling, on the other hand, can maintain a consistent temperature range. The Phase Change Material integrated stell encased cell was developed by Zhao *et al.,* [14]. In comparison to the original cell without Phase Change Material, temperature rises were 4 to 6 degrees Celsius lower. Because the heat storage capacity of a Li-ion cell is substantially smaller than that of a steel-encased cell, the PCM core's impact lowers the extreme temperature, allowing the cell to last longer. As a result, the latent heat of the PCM has a greater cooling effect. Table 2 is comparing different cooling method used by different researchers and observed result.

Table 1
Reason for low battery life and remedies

Reason behind low battery life	Remedy
Due to lithium decomposition in the edge of the anode [1]	Cathode active material should be somewhat larger than the anode active material
Contortion of electrode is not steady and would have crease and material facture [2]	Redesign the electrode
Tightening the winding process may make it difficult to completely wet the electrode and separator ports with electrolyte [3]	In winding process there should not be too much tightening
Improper design	A good design can limit the number of side reactions in the cell, extending its life
When lithium salt solute reacts with water, it produces a variety of by-products, including HF	Lithium salt solute still needs to be enhanced and created
Anode and cathode active materials molecule in size [4]	The particle size radius should be reduced
Increase in temperature [5]	Additives such as conductive agents and binders reduce the temperature
Excess rate cycling forms high power consumption in internal resistors and increases the internal temperature [6]	This can be relieved through advanced nanotechnology by carbon monotube
Extreme temperature running and its instability between the battery cell may lead to battery ageing [7]	An optimal cooling control system should be present which maintains operation range of the battery between 15-35°C, we can do this by external cooling also
Heating, short circuit, overcharge over discharge, nail penetration [8]	Cooling, proper circuitry timed charging, etc are the remedies
When a temperature sensor fails, it can provide inaccurate data to the BMS [9]	To detect faulty temperature sensor regularly
The voltage sensor defect can cause the battery's upper and lower voltage limitations to be exceeded, resulting in an internal fault of overcharge and over discharge [10]	To detect faulty voltage sensor regularly
The defect in the current sensor causes inaccurate assessment of the state of charge and other data, which has an impact on the battery management system's operation [11]	To detect faulty current sensors
Li-ion battery swelling [12]	Prevent battery form overheating, accelerated degradation and thermal runway
Overcharging causes electrochemical processes, and the loss of active material in the battery can result in the accumulation of gases inside the battery, which can lead to the battery bursting [9]	Should have a circuit breaker
Accelerated degradation of batteries is due to ageing and cell discharging [9]	Passivation of battery should be done

Table 2
Different cooling methods used for battery cooling

Method of cooling used	Result/ Outcomes
A flat heat pipe is replaced by a normal heat pipe to make contact and remove heat faster and also be steady throughout [15]	Gross temperature dispensation in the set-up was steady. While the coolant was flowing, the system's maximum temperature was reduced
For cooling, the PCM is inserted near centre of the jelly roll. (To prevent leaking, the PCM will be filled with paraffin wax and sealed [14]	Having internal cooling can make it more closed-packed oriented. Thus, enhances the energy density of the whole battery system as well as makes it thermally efficient
Set up is done in such a way that the dielectric fluid domain is immersing the Li-ion prismatic cell and excludes the Tabs. The Tabs are cooled by the forced air cooling method [16]	Better cooling with a reduction of the heat of 46.3% at 27◦C as compared to a normal natural convection battery. Also, it is a protective way for use of Li-ion batteries for high -density and capacity in Electric Vehicles
Tesla uses cold plates to cool Li-ion batteries. They designed and analysed a valve structure instead of rectangular channel to solve the coolant flow turbulent issues [17]	Provides effective cooling by lowering temperature rise and gives stability to flow
The simple model has minimal consideration on the internal battery electrochemical reaction by air cooling technique. The air-cooling design was arranged in different ways w.r.t position as well as the height of the battery pack [18]	Different positions of air-cooling structure w.r.t height and positions showed better temperature distribution throughout the battery pack
They developed a serpent cooling pathway and a U-bent shaped pathway of the channel with the cylindrical number of batteries stacked together and compared the outcomes. Second, an algorithm for serpent type cooling channel optimization was implemented [19]	Serpent type cooling channel showed more cooling effect than U bend type cooling channel and after optimization, the heat reduction reduced up to 7.5%(approx.) than initial or the base model. Also has linear temperature distribution across the battery
The prismatic battery pack in the system employs propane to lower the temperature of the cells at various C-rates. It makes use of a passive cooling system [20-22]	Propane enhances the temperature linearity of the battery pack's temperature distribution

We created and analysed the internal colling mechanism of a Li-Ion prismatic battery pack (2S-2P) for drone use after analysing various literature reviews. We redesigned the electrode with a coolant flow channel for the internal cooling system to see how effective it is in terms of temperature.

To attain the best results, the following approaches were used: Using thermal management of Li-ion batteries, the internal cooling of the prismatic battery unit will be explored.

i. Water has been utilised as a coolant for the electrode, and it will be connected to the electrolyte flow line.
ii. The highest heat generation from the transient simulation will then be used as a constant heat source and steady state simulation will be run.
iii. Obtaining heating characteristics such as cell and battery pack temperature, total heat generation rate, and transient heat generation rate Simulations using Ansys Fluent and MSMD were used. The use of maximal heating values in a steady state cooling simulation serves as a stress test for the battery to see if it can sustain heat beyond the transient heat parameters.

2. Methodology

For this analysis a Li-ion prismatic cell (EiG Eplb-C020) with dimensions of (127mm 196mm 7mm) since it has a lot of energy storage capacity and takes up less space than other cells, making it more versatile. Table 3 shows the detailed specifications.

Table 3
Li-ion prismatic cell (EiG Eplb-C020) specifications

Specification	Values
Cathode material	$LiNiCoMnO_2$
Anode material	Graphite
Electrolyte	Carbonate based
Nominal cell capacity	20AH
Nominal cell voltage	3.45V

The EiG ePLB-C020 battery has been designed in Design Modeler with exact dimensions and configuration. The cell measures 127 mm wide, 196 mm long, and 7 mm tall (thickness). The width of the positive and negative tabs is 30 mm, the length is 23 mm, and the thickness is 6 mm (thickness). The internal flow channel measures 43mm in length and is contained within a 60mm long electrode, which is followed by a separator. In the design, a separator gap of 5mm was considered. Figure 1 displays the detail of the battery design and its internal design. For series and parallel connections, busbars with a length of 10mm and a thickness of 5mm are utilised.

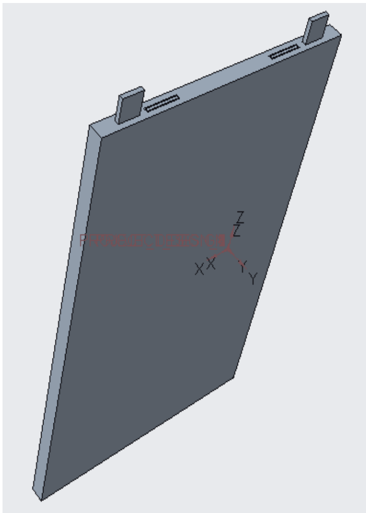

Fig. 1. 3D model of cell

As a result, the cell is analysed as a single domain rather than many domains such as electrodes, separators, and tabs.

The MSMD battery simulation is configured by entering the battery capacity, selecting the battery, tab-zones, and the positive/negative tab, as well as establishing the C-rates, inputting the stop voltage (2.6v and 4.3v, respectively), and selecting the battery, tab-zones, and the positive/negative tab.

For the density, specific heat, thermal conductivity, and electrical conductivity of the active material inside the battery cell, the values are 2092 kg/m3, 678 J/kgK, 18.4 W/mK, and 3.54 107 siemens/m, respectively. The uds-0 and uds-1 coefficients are set to 1190,000 kg/ms and 983,000 kg/ms, respectively. The chosen material for the gap between two nearby cells is air.

The simulation runs at several charging rates, such as 1C, 2C, and 3C. We're concentrating on the 3C numbers because heat generation is higher. For a 50-minute discharge duration, a transient examination of a single cell was performed, and the respective cell temperatures and total heat generation rate were recorded.

The steady state cooling simulation is started after the transient simulation is finished and the heating values are received. The battery does not deplete in this case, and so the MSMD is not initialised. Water flowing at 0.02m/s through the internal channel cools the battery, which acts as a continual heat source.

In the 3D battery cell model, we created rectangular flow channels where water flows from inlets and is divided into two different channels. Furthermore, water condenses and escapes out the outlet. The flow channels measure 43mm in width and 196mm in height. The flow channels are 2mm thick, with 0.4mm thick flow channel walls (Figure 2). The flow changes are surrounded by 60mm long electrodes with a 1mm spacing from the battery side. The dotted line represents the electrode. There is a 5-6 mm gap between them (Figure 2).

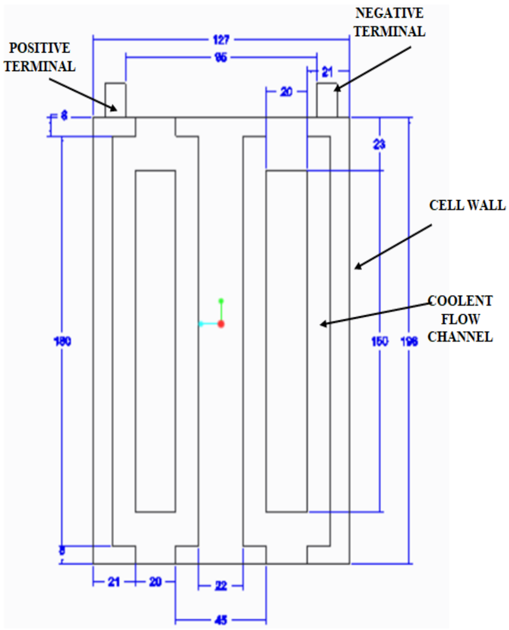

Fig. 2. External and internal view of the cell

Between the electrode and the cell boundary, there is a 1mm gap, while the separator has a 5mm gap.

Aluminium is used for the flow channel because it is a good heat conductor. The flow domain is modelled inside the cooling simulation's aluminium channel.

3. Results and Discussion

3.1 Simulation of Battery without Cooling

The simulation analysis provides insight into the heating characteristics and how much cooling capacity is required to maintain ideal battery temperatures, which ensures long battery life. For a certain prismatic battery, we are simulating a single battery at various c rates, such as 1C, 2C, and 3C. The simulation of a battery without a cooling channel is included in the following results. Following thermal analysis is carried out on 3ds Software by Dassault Systems, the temperature distribution of a single cell at various C-rates is depicted in Figure 3. The cell that is initiated at 3 C-rate is the warmest (it reaches 338K at 1000Sec) while the 1C rate battery behaves normally (315K at 300sec). As a result of Figure 3, it has been determined that cooling is required at temperatures of 3C and above. The ambient temperature was kept between 30-35°C for this study.

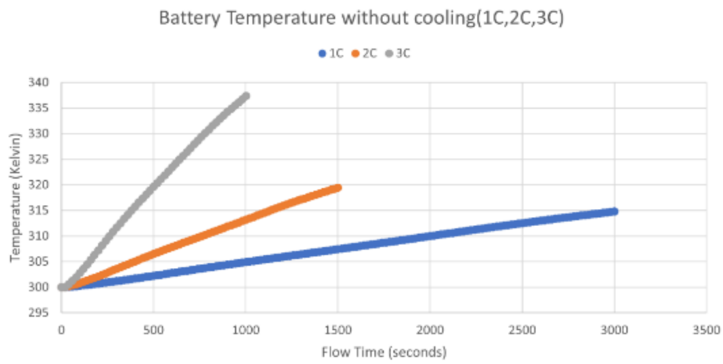

Fig. 3. The temperature of the battery

Figure 4 shows a similar pattern to Figure 3 C-rate graph, which has the maximum heat output. MSMD inhibits heavy discharge if heat creation follows an exponential trend, so the drop in heat generation is noticeable. With this study, the greatest heat generation (volume weighted average heat generation) for a 3C rate at 1000 sec was 43332.86 W/m^3.

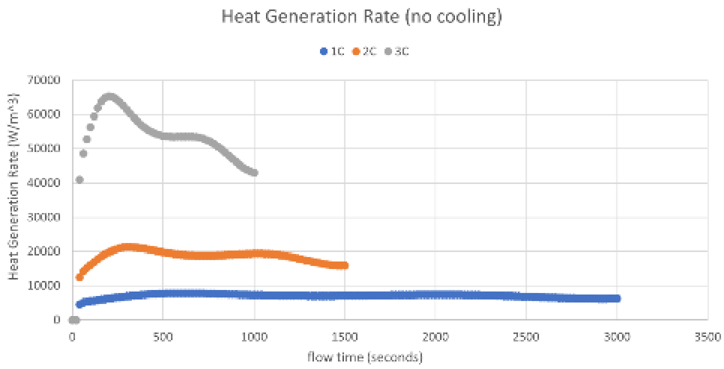

Fig. 4. Heat generation rate

3.2 Internal Cooling for Single Cell

To replicate the flow channel's cooling capabilities, the cell was tested for 800W/m^3, 1200W/m^3, 1600W/m^3, and 2000W/m^3 volume weighted average heat generation. The results were identical at higher heating settings, and the temperature drop was similar. The cell and flow channel were both heated to 300 degrees Fahrenheit at the start. Most lithium-ion batteries have a safe maximum temperature of 55°C. There is permanent damage after that. The cell's maximal heating capacity was discovered to be around 1000 W/m^3, resulting in a cell temperature of 331K or 57.85°C, which is close to the maximum allowed limit.

During 3C, the maximum temperature was 338K, as shown in Figure 3. However, after cooling, Figure 5 indicates that the temperature of a single cell remained at a maximum of 300 K, which is the optimal operating temperature for maintaining battery health.

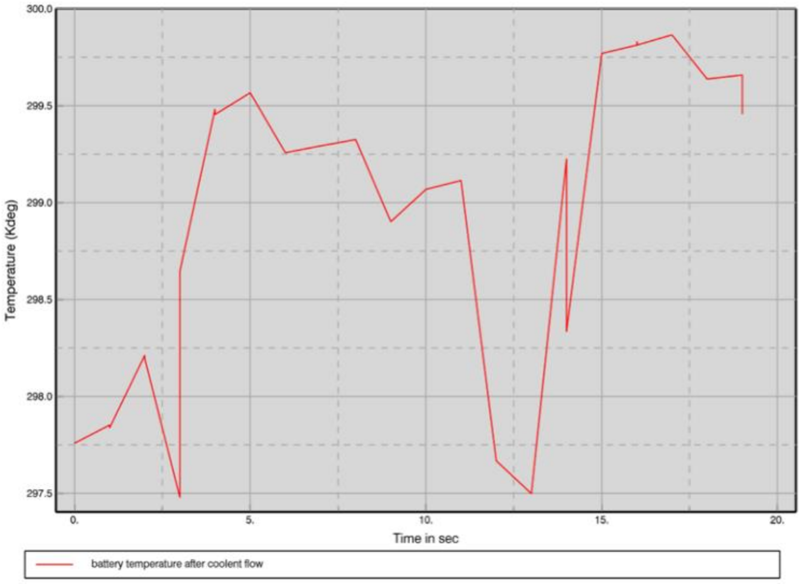

Fig. 5. Cell Temperature at heat generation rates

Along with Figure 6 represents Cell Temperature at heat generation rates path.

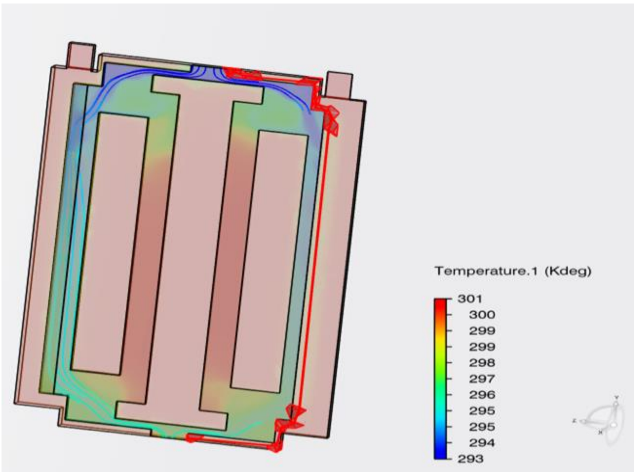

Fig. 6. Outlet temperature of cooling fluid heat generation rates

Figure 7 depicts the outlet temperature of cooling fluid at a constant flow rate under heat generating conditions in battery cooling.

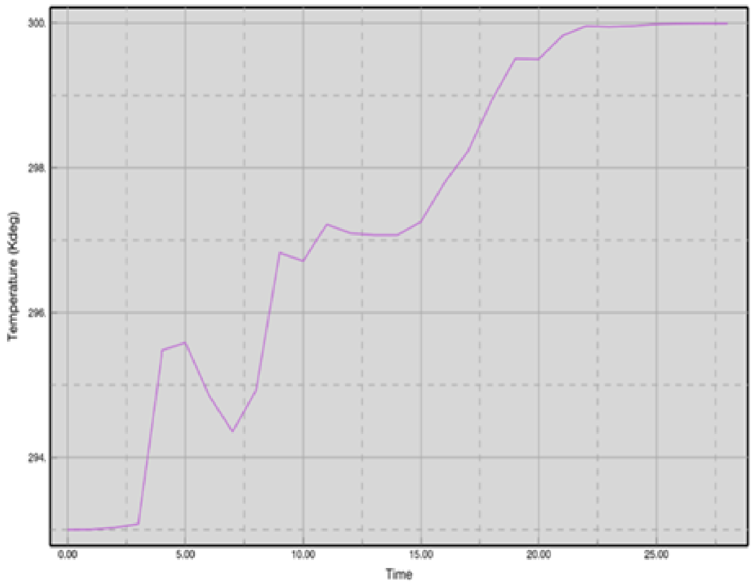

Fig. 7. Outlet temperature of cooling fluid heat generation rates

Figure 8 represents its path which is selected on software which is showed in red color line. The graphs below demonstrate the general heating trend beyond the 3-C simulation's boundaries. Higher heating conditions can be tolerated by the flow channel. Further within the simulation, the maximum cooling capacity of the flow channel will be examined.

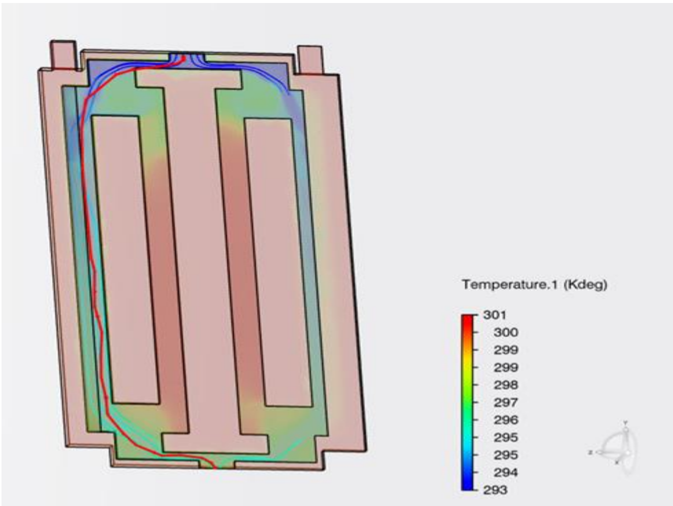

Fig. 8. Outlet temperature of cooling fluid heat generation path

Each cooling channel can thus remove 80W of heat before the cooling system loses its ability to maintain the recommended maximum cell temperature of 55°C.

The cell and outlet temperatures are also displayed to show the cooling channel's trend. Heat builds up in the cells, raising the cell temperature and, as a result, the output temperature, until the temperature stabilises and the simulation converges.

From the above thermal analysis summarized in Table 4, the following observations are made:

i. Heat Generation: Due to charging and discharging at the maximum C-rate, the heat generated inside the cell is 200 W/m³.

ii. Temperature Observations: The cell surface temperature is recorded at 331 K. The maximum fluid outlet temperature from inside the cell is observed to be 341 K.
iii. Heat Dissipation: The system has two fluid outlets for heat dissipation. The heat removed through fluid circulation is measured at 79 W and 80 W, respectively.

This analysis highlights the thermal behavior of the cell under maximum load conditions and the effectiveness of the fluid circulation system in battery inner heat management.

Table 4
Cell and outlets temperature at 200 (W/m^3) heat generation

Heat Generation Rate (W/m^3)	Cell Temperature (K)	Outlet Temperature (K)	Cell Heating (Watts)	Outlet 1 heat dissipation (Watts)	Outlet 2 heat dissipation Watts
200	331	341	159	79	80

3.3 Battery Pack Simulation of 2p2s Configuration

Design modular4 was used to model and simulate a battery pack with two series and two parallel cell configurations (2S-2P). To complete the pack connection, additional busbar was modelled for connectors. This battery pack was designed with drones in mind.

The results of the cooling simulation of a 2p2s battery pack follow the same pattern as the single cell cooling simulation, with the cell being warmer at the bottom and hotter at the top.

Figure 9 illustrates the 2p-2s configuration of the battery pack and the positioning of microchannels within the battery. Figure 10 depicts the cell temperature of the battery pack during charging at a 3C rate. The figure shows that the temperature varies between 309 K and 372 K over time.

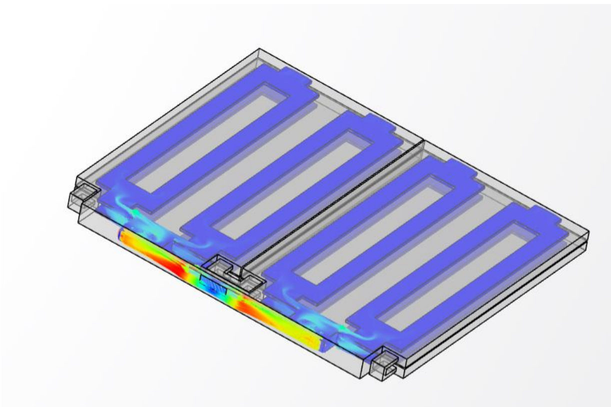

Fig. 9. 2p2s battery pack

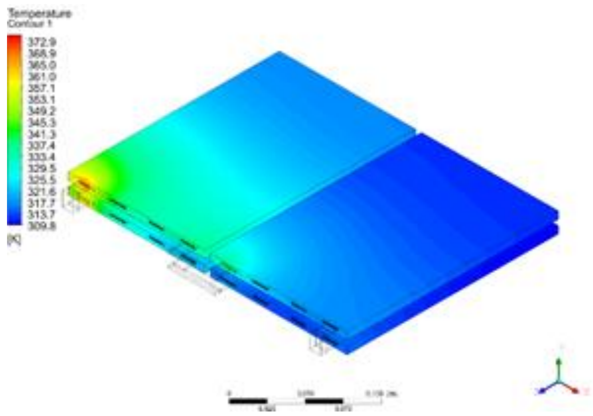

Fig. 10. 2p2s cell temperature contour

Figure 11 represents the cell temperature of the battery pack (2p-2s) after dielectric fluid flows through the microchannels within the cathode and anode. Figure 12 illustrates the temperature of the dielectric fluid flowing inside the cell. Since steady-state conditions are considered, only a minimal temperature difference has been observed.

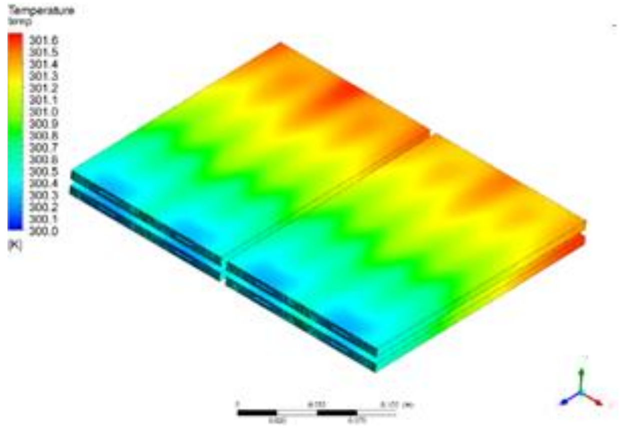

Fig. 11. 2p2s cell temperature contour after cooling

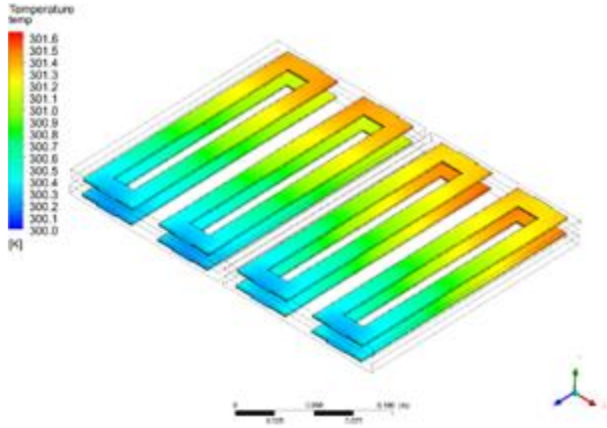

Fig. 12. Contour of flow channel temperature

Figure 13 represents the heating and cooling simulations of a single cell at different C-rates. Figure 14 illustrates the velocity profile of the cooling channels. The coolant flows at a rate of 0.02 m/s, and due to the very low velocity, the pressure drop is minimal.

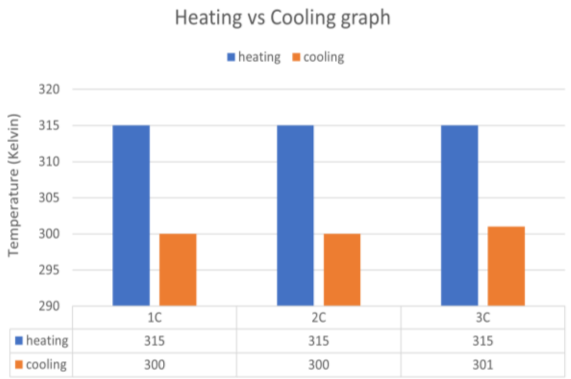

Fig. 13. Effect of cooling at 1C/2C/3C

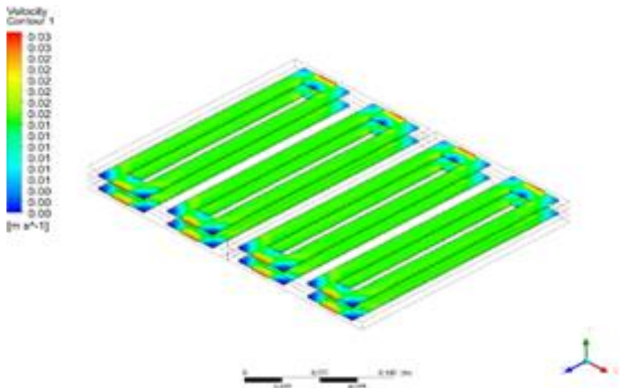

Fig. 14. Velocity contour of flow channels

4. Conclusion

At high heating conditions, the cell reached excellent cooling capacity. The main cell was pushed to its maximum cooling capacity using the 2p2s pack design, which achieved optimal cooling temperatures.

Each cooling channel (there are two per cell) can dissipate 80W of heat from the cell, while the cooling channel as a whole can absorb under 160W of heat.

Under ideal temperatures, the simulation reveals a stable battery cell that can discharge at 3C. The 20Ah cell was heated to 1°C, 2°C, and 3°C, then cooled at the same C-rates. The temperature dropped by about 20°C on average.

The results of the simulation above provide us with an idea of internal cooling that can withstand severe temperatures. As a result, a higher-power battery pack can be modified for high C-rate operation at ideal battery conditions.

The lifespan of the cell can be greatly increased by employing an internally cooled thermal management system because the cell was at the optimal working temperature.

Because of its high cooling capacity, the cell can be used in high-power EV and electrical equipment applications. Further cell modelling would necessitate an experimental setup as well as a lot of computing resources to mimic.

Because the general trend of heating is linear, predictive modelling can be used. To improve safety and absorb more heat from the aluminium wall, the cell can be cooled with a non-reactive coolant with high latent heat.

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