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Research Progress of Battery Thermal Management Systems with Minichannels

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ABSTRACT. With the developing technology, energy storage systems, especially lithium-ion batteries (LiBs), play a critical role in electric vehicles and renewable energy applications. However, the performance and life of batteries are significantly affected by their operating temperatures. In this context, battery thermal management systems (BTMS) are of vital importance to ensure temperature control of batteries and to create a safe operating environment. BTMSs are divided into main two groups active and passive which require and does not require extra energy consumption, respectively. In this review, the basic principles, design criteria and application areas of battery thermal management systems are examined. First of all, the components of BTMS, passive and active cooling methods, heat dissipation and temperature monitoring techniques are detailed. In addition, the effects of different BTMS approaches on efficiency and performance are compared. The analysis of existing studies in the literature reveals the positive contributions of BTMS on battery life, charge-discharge efficiency and safety. In addition, future research areas and development opportunities are also highlighted. In conclusion, an effective thermal management system is a critical factor in the development of battery technology and has great potential in terms of sustainability of energy systems.

Keywords: Electric Vehicles, Li-ion Batteries, Battery Thermal Management Systems, Minichannels

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1. INTRODUCTION

The world's population is increasing and people prefer city centers as their living space. It is predicted that the world population will be 9.1 billion in 2050 and 80% of the world's population will live in cities. Such large populations living together causes some problems and affects the quality of life. Some of these problems are noise and environmental pollution. Exhaust emissions from transportation vehicles are increasing and triggering environmental pollution. In the next stage, it becomes one of the causes of global warming and climate change. [1,2]

As a solution to the environmental problems caused by automobiles, internal combustion vehicle emissions had to be gradually reduced and reduced to zero. In order to combat climate change, the European Union (EU) made it mandatory for new cars and light commercial vehicles to be zero-emission after 2035. [3]

Electric vehicles (EVs) and hybrid electric vehicles (HEVs) are two methods we encounter to achieve zero-emission targets. Electric vehicles operate by transferring energy from the battery pack to the wheels via an electric motor. In this way, they do not emit emissions and operate without noise. However, long charging times and short ranges are the biggest obstacles to electric vehicles. For this reason, hybrid electric vehicles (HEVs) are offered as an intermediate product in the transition period to electric vehicles. The concept of hybrid refers to the use of 2 or more energy sources together. The most common HEVs are a combination of an electric motor and an internal combustion engine (ICE). The ICE powers the vehicle when needed, while the electric motor alone powers the vehicle when not needed. This makes them more economical and cleaner than internal combustion engine vehicles. HEVs are a good alternative to EVs because they do not require long charging times and do not have a range limitation. However, it should be noted that HEVs cannot provide zero-emission values. [4]

Li-ion batteries are used as a power source in electric vehicles. Compared to other energy storage systems, LiBs is superior to others due to its rechargeability, higher power and energy density, light weight and long life. [5] The batteries to be used in electric vehicles are required to cover

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minimum space, lightweight and provide high performance while also being reliable. LiBs comes in 3 different forms: pouch, prismatic and cylindrical. While cylindrical and prismatic batteries are generally preferred in electric vehicles, pouch batteries are also used. They have superior aspects compared to each other. Cylindrical batteries are shaped by laying the anode, separator and cathode flat and then folding them like a carpet. Cylindrical batteries are easier to manufacture, have lower production costs, and are suitable for mass production. Due to their small size and high contact area, cylindrical cells have good thermal management. Prismatic cells are generally larger than cylindrical cells. They tend to have higher energy density compared to cylindrical batteries but less charge and discharge power. [6].

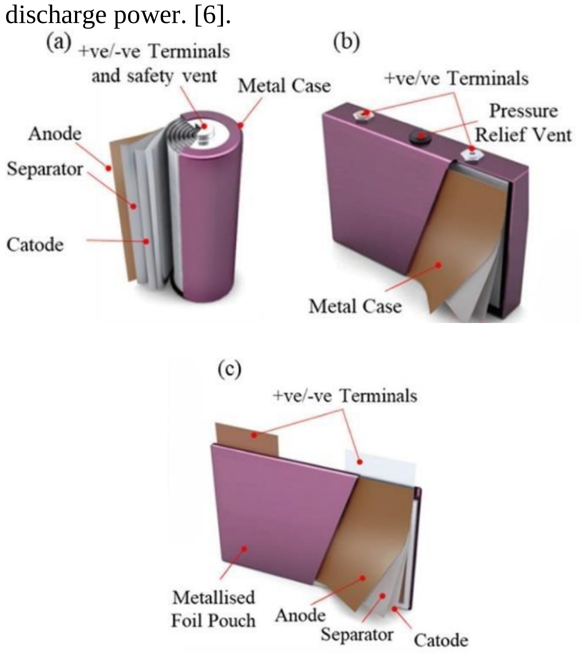

Fig. 1. Different type of batteries (a) Cylindrical (b)Prismatic (c)Pouch [7]

In LiBs, heat is generated due to internal electrochemical reactions during charging and discharging. Heat generation will increase the battery temperature. The increased temperature should be kept within certain levels (15℃ – 40℃) and the temperature difference across the LiB should not exceed 5℃. When these limits are exceeded, a phenomenon called thermal runaway occurs in the battery. Thermal runaway can cause the temperature to increase suddenly, the battery to burn or even explode. To prevent this, battery thermal management (BTMS) is essential. [8]

Cooling in batteries is done as active, passive and hybrid. In the active cooling method, which requires additional energy to operate, the coolant provides heat removal from the batteries with a pump or fan. Cooling with phase change material (PCM), heat pipe (HP) and thermoelectric cooler (TEC) is defined as passive cooling because it does not require an energy source. In hybrid cooling, active and passive cooling are combined. [9]

In this study, the latest developments related to BTMS using mini channels, which is one of the active cooling methods in thermal management of cylindrical and prismatic li-ion batteries used in electric vehicles, were examined. The results showed that the use of mini channels gave very good results in controlling the temperature.

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2. BATTERY HEAT GENERATION MECHANISM

LiBs store energy with electrons. When desired, the movement of these electrons allows the stored energy to be used in the desired place. The movement of electrons occurs due to the potential difference between the negative and positive regions. When examined in their internal structure, a LiB consists of 3 main parts: anode (negative electrode), cathode (positive electrode) and separator. In the resting state, lithium and electron remain together in the anode region. Electron and lithium movement begins during battery discharge. While electrons pass through a circuit from the negative current collector to the positive current collector and reach the anode region, lithium ions pass through the separator and reach the anode region. The separator does not allow electron passage, otherwise a short circuit occurs. However, lithium can pass through the separator. In addition, lithium is provided with a movement environment with the electrolyte material added to the battery. During charging, lithium in the cathode region passes through the separator and recombines with electrons in the anode region. If all of the lithium in the cathode region passes to the anode region, it means that the battery is fully charged. Thanks to this movement of lithium, LiBs gain rechargeable properties. During these processes, heat is generated within the battery, causing the battery temperature to increase. If the generated heat cannot be removed from the battery, a phenomenon called thermal runaway occurs due to uncontrolled lithium and electron movement. As a result of this event, the battery temperature suddenly increases 6-7 times, causing smoke and flame formation, and eventually the battery may explode. Therefore, battery thermal management is essential to prevent negative situations from occurring. [10, 11]

3. BATTERY THERMAL MANAGEMENT WITH MINICHANNELS

As mentioned above in chapter 2, thermal management of batteries is essential. For this reason, many active, passive and hybrid BTMS designs have been made by researchers. In this article, recent studies on the use of mini channels in cylindrical and prismatic battery thermal management has been reviewed.

3.1 Cylindrical Battery Thermal Managements

Heat transfer between the fluid and the solid surface is calculated from Newton's Law of Cooling, which is formulated as,

$$Q=h\times A\times dT \tag{1}$$

Wiriyasart et al. [12] numerically investigated the pressure drop and temperature distribution of a pack containing 444 cylindrical 18650 LiB under different cooling conditions. The cases where nanofluid was used and not used at three different mass flow rates and 3 different flow directions were investigated. It was assumed that there was a constant heat flux value of 3330 W/m^2 from the contact surface between the battery and the mini channel. The average battery temperature remained below 35°C in the case of underflow and overflow in different directions. The results showed that the battery surface temperature decreased as the coolant mass flow rate increased. However, there was a limit to this temperature drop and the pressure drop increased with the increasing mass flow rate. In the study, TiO2 nanoparticles were added at 0.25% and 0.5% by volume and it was observed that the battery temperature decreased. It was suggested that the battery surface temperature could be reduced by further increasing the nanoparticle ratio.

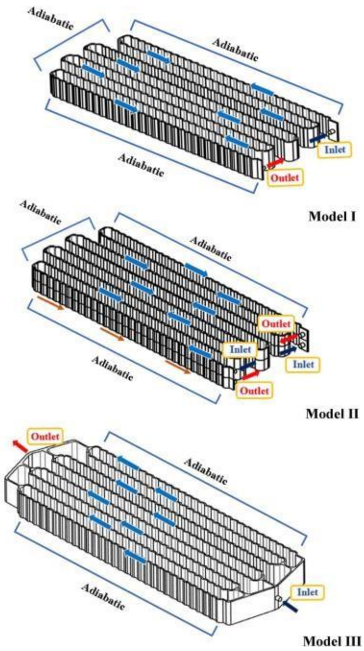

Fig. 2. Serpentine Mini Channel for 444 Cylindrical LiBs [12]

Xu et al. [13] conducted thermal analysis of 32 18650 LiB modules. Since the coolant temperature increases in the flow direction, the heat rejection rate of the package decreases. In order to prevent this, they aimed for a lightweight and uniform battery pack temperature with a wrench-shaped cold plate with a min-channel inside. The ambient temperature and fluid (water) inlet temperature were selected as 25°C. Analyses were performed for a discharge rate of 3C when water entered the channel at 0.1 m/s. As a result of the numerical analysis, it was seen that the wrench-shaped cold plate among 4 different designs provided the desired battery temperature values, with a maximum battery temperature of 30.32°C and a maximum temperature difference of 3.83°C. It was also noted that the weight was reduced by 19.68% in the wrench-shaped cold plate design. In addition, the pressure drop in this design was at the lowest level with 43.64 Pa compared to the others. The effect of the starting point of the bifurcation on the temperature for the wrench-shaped design was also examined. The results showed that starting the bifurcation after the 4th cell (8 cells in total) provided the most effective cooling. While starting the bifurcation early reduced the pressure drop, it will increase the weight.

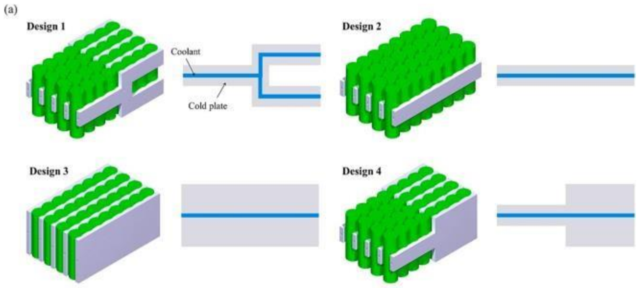

Fig. 3. Wrench Shaped Mini Channel Cold Plate [13]

Wang et al. [14] have conducted experimental and numerical studies. In the study that carried out with liquid cooled aluminium plate, they investigated the thermal behaviour of modular 18650 LiB system in mass flow and series and parallel cases. It was aimed to transfer the heat generated in the battery to the fluid through the aluminium in contact with the batteries. Water was used as coolant with laminar flow. When the mass flow rate was between 20-140 ml/min, it was observed that the maximum temperature and temperature difference decreased as the flow rate increased. However, when the flow rate was greater than 80 ml/min, the temperature drop rate decreased. In the analyses carried out with parallel cooling, the maximum temperature and temperature difference were 37.67°C and 5.76°C, while these values were 7.55°C and 6.74°C lower compared to series cooling. Therefore, parallel cooling is quite effective compared to series cooling. Finally, the effect of flow direction on parallel cooling was investigated and the maximum temperature was 37.74°C while the temperature difference was noted as 4.17°C. Considering that the ambient temperature and fluid temperature were 30°C throughout the experiment, the obtained data are quite satisfactory.

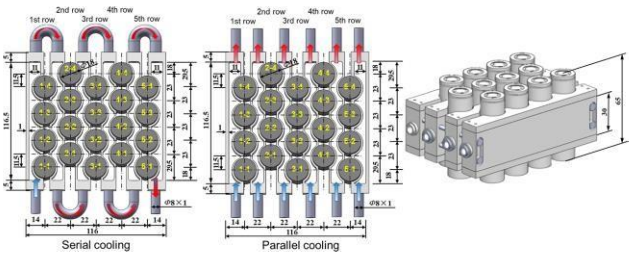

Fig. 4. Aluminium Cold Plate [14]

Wang et al. [11] investigated the combined use of PCM and mini channel with the design called hybrid wavy mini channel cold plate (HWMCP). They numerically investigated the temperature distribution of the battery at different discharge rates, PCM thickness, coolant mass flow rate, different flow directions and different array combinations. The analysis consisted of 33 18650 LiB as battery modules. Water and composite RT44HC/expanded graphite were selected as coolant and PCM. In order to compare the effect of the presence of PCM, analyses were performed on wavy mini channel cold plate (WMCP) and HWMCP with only water flow. When comparing HWMCP and WMCP, results were obtained for water mass flow rate of 0.001kg/s and battery discharge rates of 3C and 5C. Although the mass flow rate of water decreased with the replacement of water with PCM, the maximum temperature decreased by 0.8K and 1.3K with HWMCP, respectively. In addition, 90% of PCM melted at the end of 5C discharge rate, while 40% melted at 3C discharge rate. PCM did not melt until 400th second at 3C discharge rate. For this reason, maximum temperature increased. However, temperature HWMCP showed more effective results with the melting of PCM. The effect of flow direction and flow rate was also examined for PCM thickness of 4 mm and number of channels through which water passes as 6. In case of 3 flows at the top and 3 flows at the bottom in different directions, there was a 4.4K decrease in maximum temperature compared to flow in one direction. In addition, maximum temperature difference was 1.3K. Analyses were performed in cases where flow rate was 0.0010 kg/s, 0.0012 kg/s, 0.0014 kg/s, 0.0016 kg/s. When the flow rate was increased from 0.0010 kg/s to 0.0016 kg/s, the maximum temperature decreased from 328.2K to 323.3K. The reason for this high temperature is that PCM did not melt. Only 8% of PCM melted at 0.0016 kg/s. The effect of early melting was investigated with PCM having 3 different phase change temperatures. In the previous analysis, the phase change temperature was 314K-317K, while the maximum temperature decreased by more than 1K when the phase change temperature was 306K-309K. This showed the effect of PCM melting temperature on the maximum battery temperature. The results showed that HWMCP provided better thermal management than WMCP. However, it should be noted that the battery temperature above 50°C increases the possibility of thermal runaway.

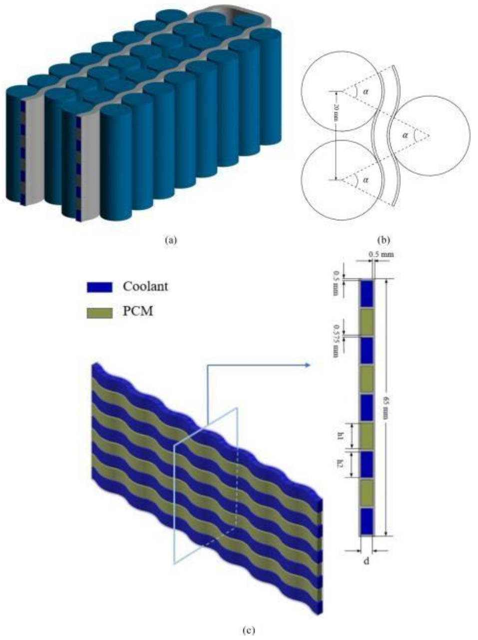

Fig. 5. PCM and Liquid Cooling with Serpentine Mini Channel [15]

Li et al. [16] performed thermal analysis of a battery pack containing 24 cylindrical 18650 LiB. They used a heat conducting block (HCB) through which coolant (water) passes for heat dissipation. The channel through which water passes is 6 pieces of 1 mm x 4 mm dimensions. Other boundary conditions are as follows: ambient temperature between 25°C and 45°C; water flow rate 0.4 m/s; water temperature 25°C; discharge rate 2C. In the analysis performed at 45°C ambient temperature, the battery temperature dropped below 30°C after 50 seconds. Since the heat dissipation from the batteries was too much, the discharge rate was insufficient to heat the battery. For this reason, the maximum battery temperature remained constant. The effect of water inlet temperatures was also investigated in the cases where the ambient temperature was 35°C and 45°C. In all cases, while the maximum temperature difference remained below 5°C, the possibility of thermal runaway increased when the water inlet temperature exceeded 35°C. As a result, due to the 135° contact angle between the HCB and the battery, the high heat transfer rate of the HCB and the high water inlet velocities, a very effective cooling was achieved and quite satisfactory temperature values were obtained despite the extreme conditions.

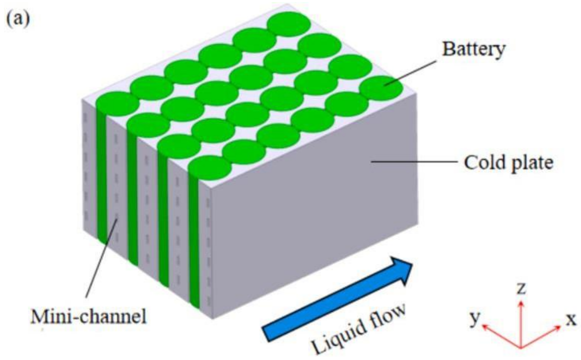

Fig. 6. Mini Channel Cold Plate Cooling with 24 LiB [16]

Xin et al. [17] numerically investigated the temperature, weight and power consumption effects of air and water cooled 32 pieces of 18650 LiBs with different flow rates and geometries at 3C discharge rate. A heat conducting block (HCB) with cooler passing through it was used as the heat transfer element. Analyses were performed under with 2, 3 and 4 HCBs; 4mm, 6mm, 8mm and 10mm fluid diameters and constant mass flow rate conditions. It was concluded that 6 mm pipe diameter was the most suitable for HCB. In the analyses with 2 and 3 HCBs, the effect of the pipe diameter on the temperature was minimal. Considering the maximum temperature, temperature difference and pressure drop, 3 HCBs were preferred.

Analyses were made for the case where there was no flow in the HCB and for the case where there was flow with 7 different flow rates. Since the temperature difference between the water and the battery was low at the beginning of the discharge process, the amount of heat transfer was low. For this reason, a rapid increase in the battery temperature was observed. Over time, the temperature gradient increased and as a result, the maximum temperature came to equilibrium. While the increase in the flow rate reduces the maximum temperature, the rate of decrease in the temperature decreases. This shows that it is unreasonable to increase the flow rate too much.

Although the water keeps the maximum battery temperature below 35°C, the battery temperature difference is over 5°C. In order to prevent this, the researchers have made an analysis for additional air cooling. In addition to the constant conditions of 6 mm pipe diameter, 0.002 kg/s mass flow rate and 3 HCBs, analyses were made for air at different velocities. For an air mass flow rate of 1 m/s, the maximum temperature was 30.67°C and the temperature difference was 0.58°C. Though these results are very successful in preventing thermal runaway, it should be taken into account that energy consumption increases.

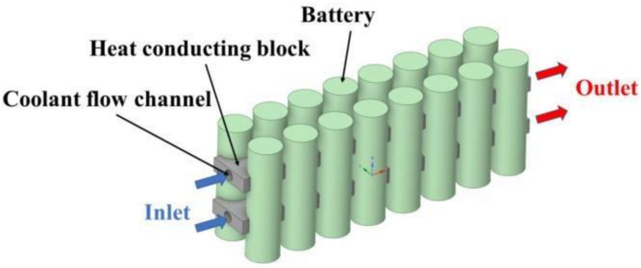

Fig. 7. Air and Liquid Cooling HCB [17]

3.2 Prismatic Battery Thermal Managements

Mini channel provides the desired cooling requirement while occupying a minimum volume in prismatic batteries. Efforts to increase heat transfer in prismatic batteries focus on the use of mini channels with different shapes and different attachments. In this section, recent studies on mini channels in prismatic batteries are compiled.

Dilbaz et al. [18] numerically performed the thermal analysis of 3 prismatic batteries with a capacity of 20Ah in their study with phase change material (PCM) and mini channel cooler. A rather extensive investigation was carried out in the cases of 3 different discharge rates (2C, 3C, 4C); water and Al2O3 nanoparticle added (0.5%, 1% and 2% by volume) nanofluid; 4 different geometry nanoparticles (Oblate spheroid, block, cylinder, and platelet); 4 different Reynolds numbers (250, 500, 750, 1000). The maximum temperature and maximum temperature difference were targeted to be below 50°C and 5°C in the study. In the analyses, when only RT-42 PCM was used at 4C discharge rate, maximum battery temperature and maximum temperature difference were 45.736°C and 1.96°C, while 100% of PCM melted at 260 seconds. Analyses were performed when PCM and serpentine mini channel (diameter 1.5 mm) were used together. At 3C discharge rate, when Re number was 500 and platelet-shaped 2% Al_2O_3 nanofluid added coolant was used, the maximum temperature was obtained as 47.85°C. It was determined that platelet-shaped nanofluid gave the best result among other nanofluids.

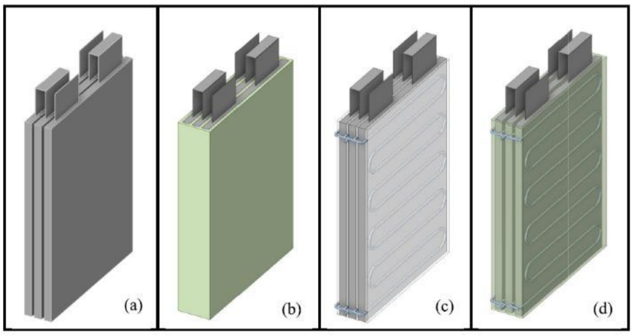

Fig. 8. PCM and Serpentine Mini Channel Cooling [18]

Jaffal et al. [19] performed experimental and numerical analysis of prismatic battery for 1C and 2C discharge range, 45°, 60°, 75° and 80° rib angles and semi-circular (SCR), trapezoidal (TRAP), and triangular (TRAN) rib shapes. The reason for using ribs is to disrupt the boundary layer and improve heat transfer. The flow Reynolds number is designed between 200 and 1000 and the cross-sectional length of the channel through which the fluid passes is 4 mm×5 mm. Heat transfer from battery to the channel is performed with constant heat flux.

CFD analyses were first performed on 4 different angles of semi-circular shaped ribs (SCR), at 800 Reynolds number and 1C discharge rate. The best result among them was obtained as 27.46°C for SCCP-SCR-45°. In the analyses where the Reynolds number was increased, better cooling was provided and temperature uniformity was provided. It was also determined that decreasing the rib angle improved heat transfer and ensured that the maximum temperature difference of the battery was at the desired levels. At 1000 Reynolds number and 45° rib angle, the Nusselt number increased by 58% compared to the empty channel. Knowing how much the pressure drop is while such large increases in heat transfer are provided will be important for the efficiency of the ribs. The friction factor decreased as the Reynolds number increased. However, decreasing the rib angle increased the friction factor. Compared to the flow without ribs, the 45° rib angle at 100 Reynolds number caused the friction factor to increase by 106%.

To investigate the effect of rib shapes on heat transfer, and pressure drop analyses were performed for the channel at 45° rib angle. The results showed that the SCCP-TRAN-45° design gave the best results. It was also noted that the Nusselt number increased by approximately 71%, while the overall hydrothermal performance increased by 30%.

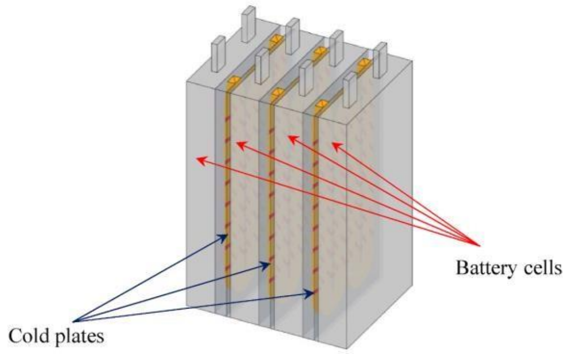

Fig. 9. Effect of Different Ange Ribs [19]

Zhao et al. [20] numerically analysed 10 LiFePO4 prismatic batteries with honeycomb liquid cooled cold plate (HLCP) design to determine the thermal behaviour. At the beginning of the analysis, the ambient temperature, coolant temperature and battery temperatures were input as 298.15K and the flow character was laminar. Three different honeycomb geometries of HLCP with 3mm channel height and 8mm channel width were designed. The analysis results at 5C discharge rate and 0.1m/s velocity inlet showed that the maximum battery temperature was lower than 304K with case 3, while the maximum battery temperature difference was 4.1K.

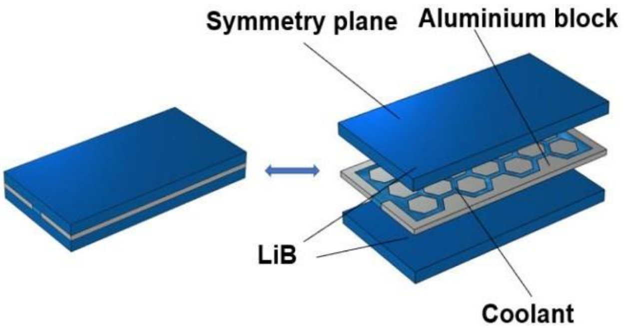

Fig. 10. Honeycomb Shaped Mini Channel Cold Plate [20]

Analyses were performed for 5 different cases where the coolant entered the channel from 1, 2 and 3 points. In the first 3 cases, the inlet velocity was reduced as the number of channels increased to maintain the total flow rate. The velocities in Case4 and Case5 were designed as 0.2m/s and 0.3m/s. The results showed that the maximum temperature did not depend on the increase in the number of inlet points. However, it was observed that the maximum temperature difference decreased if the number of inlet points increased. But, since this decrease was not significant, it was not taken into account in further analyses. The maximum temperature decreased to 300.6K by increasing the velocity to 0.3m/s. In order to better understand the effect of velocity, analyses were performed for 6 different inlet velocity values ranging from 0.01m/s to 0.5m/s. The results showed that increasing the inlet velocity more than 0.3m/s did not contribute significantly to the battery thermal management. In addition, the analysis performed on increasing the thickness of the HLCP showed that increasing the thickness without changing the flow rate did not contribute significantly to heat dissipation. Finally, it was observed that the flow direction had no effect on reducing the maximum temperature, but was successful in achieving a uniform temperature distribution. As a result, the importance and effectiveness of mini channel use in thermal management of prismatic LiBs was revealed.

Li et al. [21] numerically investigated the effect of a new type of pin-fin added mini channel cold plate on battery thermal management performance increase. Prismatic LiB with a capacity of 45Ah was selected as the battery, which will serve as heat generator in the battery package. A design was proposed in which the coolant enters the mini channel from 5 different points and flows in parallel. The mini channel section lengths were 3mm×8mm, while the cold plate thickness was analysed as 4mm. CFD analyses were performed for coolant inlet temperature, pin-fin heights (PFH) and different pin-fin arrangements. In the analyses, the maximum battery temperature increase, maximum battery temperature difference and pressure drop were examined and the pin-fin efficiency performance was investigated.

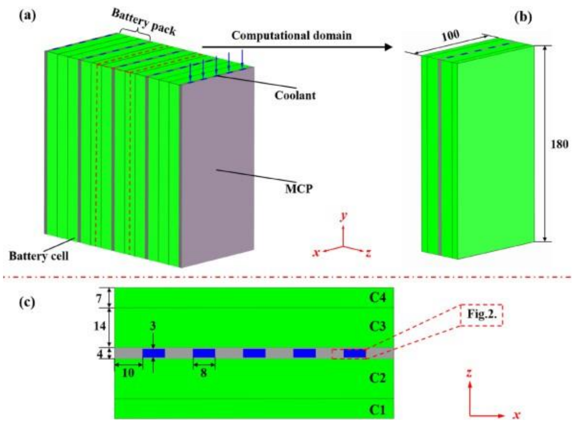

Fig. 11. Pin-fin Added Mini Channel Cold Plate [21]

Analyses were performed with the fluid at 3C discharge rate and 0.1m/s constant velocity in the mini channel without pin-fin (D1) and with pin-fin (D2, D3, D4, D5, D6). In the analysis, the ambient, battery and coolant channel inlet temperatures were selected as 298.15K. The results showed that the fluid velocity increased as the PFH increased, as expected, since the cross-section narrowed. In addition, the pin-fin increased the fluid contact surface area and improved the heat transfer. For more detailed examination, analyses were performed at 2C and 3C discharge rates with 0.1m/s and 0.4m/s fluid velocities. It was noted that the D2 design, which has the highest pin-fin height, reduced the maximum battery temperature by 4.822K at 0.4m/s and 3C discharge rate compared to D1. In the analysis performed at 2C discharge rate and 0.4m/s velocity, the maximum battery temperature difference remained below 5K in the all pin-fin arrangement analyses except D6. This value was 5.09K for D6 and 4.139K for D2.

The effect of Nusselt number and fanning-friction factor was also examined together to calculate the performance efficiency. In the analysis performed at 0.1 m/s inlet velocity, it was calculated that D2 design increased the Nusselt number by 83% compared to D1, but the fanning-friction factor increased by 238.9%. Therefore, heat transfer and friction coefficient should be evaluated together. The thermo-hydraulic performance of the best result D4 design was determined as 1.2935 and 1.4851 at 0.1 m/s and 0.4 m/s inlet velocities, respectively. With this result, the effectiveness of pin-fin usage in mini-channel battery thermal management was demonstrated.

3. CONCLUSIONS

This paper compiles the latest studies on the use of mini channels in thermal management of LiBs. The results obtained are as follows;

–Mini channels took up very little space while transferring heat from the battery. Therefore, it’s quite appropriate for battery packs.

–The efficiency coefficient increased by placing heat transfer enhancing elements (pin-fin, nanoparticle) inside the mini channel.

–Uniform battery temperature could be achieved by adjusting the fluid direction. However, its effect on the maximum temperature was minimal.

–As the fluid flow rate increased, the battery temperature approached a limit value and increasing the flow rate too much negatively affects power consumption.

–It has been shown that effective cooling is achieved by using high heat conduction blocks with mini channels which coolant passes through in it.

–Among the reviewed articles, Wang et al., PCM and Liquid Cooling with Serpentine Mini Channel, was considered to be the most original study.

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