Hybrid Thermal Management Systems for Lithium-ion Battery-based Electric Vehicles: A Review

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Abstract

The temperature of lithium-ion batteries has a significant impact on both their safety and performance. To achieve optimal performance and mitigate safety risks, these batteries must operate within a specific temperature range of 20°C to 40°C and temperature difference less than 5°C. Although manufacturers first used single thermal management systems, these systems are particularly suited for low-rate charge/discharge rates. However, today's requirements aim to decrease the time of charge/discharge. In other terms, increase the rate of charge/discharge. This increases the rate of heat generation inside the battery. Therefore, it is crucial to develop more effective thermal management systems that can meet these requirements. A promising approach involves combining two or more single management systems into a hybrid system. The main purpose of this review is to hold a comparison between different hybrid thermal management systems based on the maximum temperature difference, maximum temperature, and feasibility of application of these systems in real life. After studying these systems, it was found that the hybrid system that combines heat pipes, composite silica gel plate (CSGP), and Liquid cooling showed high performance at a high discharge rate of 4-C. The system could keep the maximum temperatures below 43.5°C and maximum temperature differences below 3.5 °C, at water velocity of 0.2 m/sec. Furthermore, the system is not complex, which facilitate its implementation in electric vehicles.

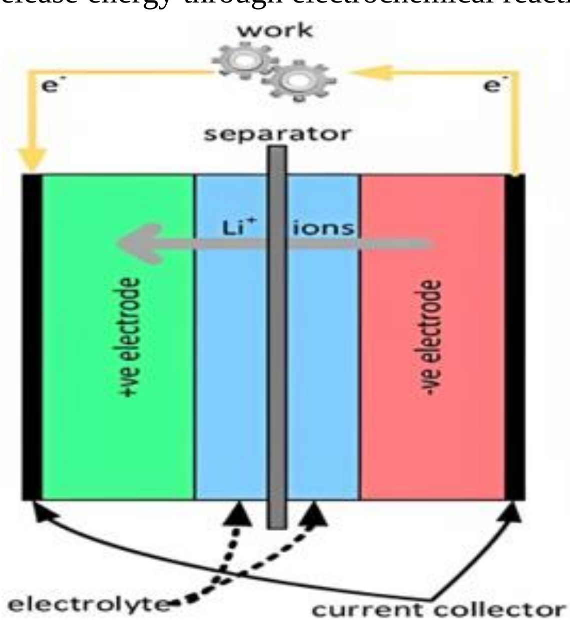
Index Terms—Lithium-ion battery, charging rate, thermal runaway, single thermal management system, hybrid thermal management system.

I. Introduction

According to the European Union Commission, petrol- driven vehicles are responsible for 17% of the total greenhouse emissions, and about 72% of greenhouse emissions emitted from transportation [1]. Therefore, there is a rising need for more effective and environmentally friendly road vehicles. Electric cars offer a potentially effective way to cut carbon emissions [2]. However, in 2020, these vehicles only accounted for 2.8% of the market [3]. The primary problem that prevents electric vehicles from becoming widely used is the safety hazard brought on by heat generation during charging and dis- charging cycles. In addition to safety hazards, the unregulated temperature has an impact on capacity and performance. When the temperature reaches 40 °C, the amount of power that can be given is 1.25% less than when the battery is operating at 20 °C. Furthermore, power supply capacity loses 1.5% to 2% more if the battery's internal temperature gradient exceeds 5 °C [4]. Therefore, it is crucial to develop a heat management system that can control the temperature within an optimal range of 20◦C to 40 °C and a temperature difference of 5 °C [5]. Electric car manufacturers initially used single-heat management systems. Air-cooling systems, liquid cooling systems, phase change materials, and heat pipes are the main single management systems. The air-cooling system is size-limited and cost-effective. However, this system is unreliable at high discharge rates because of air's limited thermal conductivity and specific heat capacity. On the contrary, the liquid cooling system has a higher cooling capacity. However, the system exhibits drawbacks such as complex structure, high cost, and potential leakage problems. Phase Change Material (PCM) is a highly effective single-cooling technique. PCM works by absorbing heat to undergo phase change while maintaining a constant temperature. However, these materials can run out of latent heat after successive charge/discharge cycles. To balance the advantages and disadvantages of the above thermal management systems, manufacturers have considered hybrid thermal management systems. These systems are combinations of two or more of the single thermal management systems discussed above to optimize the mass, volume, cost, and thermal performance of the system [6]. This review's objective is to compare the various hybrid thermal management systems based on maximum temperature, maximum temperature difference, and system viability on a wide scale. The mechanism of lithium-ion batteries, the sources of heat loss, single heat management systems, and hybrid systems will all be covered in this review.

II. LITHIUM-ION BATTERY

Lithium-based systems open a new way for high-power batteries, replacing old battery technologies such as lead–acid and nickel-based batteries [7]. Lithium-ion batteries are built up from several electrochemical cells working in conjunction with one another. These electrochemical cells can store or release energy through electrochemical reactions.



A typical Li-ion battery cell is composed of an anode, a cathode, electrolyte and separator, as shown in Fig. 1 [8].

i. Positive electrodes

Positive electrodes are intercalation compounds from which Li+ ions can diffuse out or back. This can affect battery performance. Lithium Iron Phosphate, Lithium Nickel Manganese Cobalt Oxide, and Lithium Nickel Cobalt Aluminum Oxide are examples of commonly used positive electrodes

1) *Lithium Iron Phosphate ($LiFePO_4$):*.

This electrode's market in electric vehicles reached 31%, and 68% of that was from Tesla and Chinese EV maker BYD production alone. In addition, the electrode offers long life span. It can support more than 3000 cycles. Also, it is cost effective, as it does not include high-cost Cobalt [9]. This electrode can work under a wide temperature range of $-30^\circ C$ to $60^\circ C$, and consequently, reducing the chance of thermal runaway, which would be described later. However, this electrode faces some drawbacks such as high self-discharge rates that can cause balancing issues [10].

2) Lithium Nickel Manganese Cobalt Oxide:

Lithium Nickel Manganese Cobalt Oxide electrodes can be designed for high specific energy or power with high density. Researchers increase nickel content to increase the energy density of the battery and reduce cobalt to lower the cost of production. This electrode has been used by many manufacturers, including Nissan Leaf, Chevy Volt, and BMW I3 [11][12].

3) Lithium Nickel Cobalt Aluminum Oxide

Lithium Nickel Cobalt Aluminum Oxide Li(NixCoyAl)O2 shares similarities with Lithium Nickel Manganese Cobalt Oxide electrodes. This electrode offers high specific energy of 279 mAh/g, and a long-life span. However, by increasing the Nickle content, some safety issues will appear. As the temperature increases to 180◦C it will thermally run away. If the battery was previously overcharged, thermal run away can occur even at low temperature as 65◦C. In addition, it is not cost-effective, due to large cobalt content [13]. Tesla is the only manufacturer that uses this electrode in Tesla Model 3 and the first Model S in 2012[14].

ii. Negative electrode

There are two types of negative electrodes: lithium titanate and carbon-based electrodes.

1) Carbon Based Electrodes:

Carbon based electrodes are the most commonly used negative electrode, due to their relatively high specific capacity of 370Ahkg−1. In addition, this electrode has a low average voltage (150 mV vs. Li/Li+). The low average voltage is a measure of the difference between the standard Li-ion battery and the actual potential. Furthermore, this electrode is relatively cost-effective and non-toxic. Regrettably, this electrode has some safety concerns, as it can react with atmospheric air causing thermal runaway, which would be discussed later [14].

2) Lithium Titanate

Li-titanate (Li4Ti5O12) replaces graphite in the negative electrode of a Li-ion battery. The volume of this electrode is constant overcharging and discharging processes. Therefore, it offers a long lifespan. However, this material has low electrical conductivity (< 1013cm−1) and low Li+ diffusion coefficient that results in poor performance at high discharge-charge rates. This could be improved through doping, surface coating, and forming composites with better electronic conductors such as carbon materials [15]. This type of electrode is being used in Mitsubishi’s i-MiEV electric vehicle, Tesla electric bus, and mobile medical devices.

iii. Electrolyte

The electrolyte is an important part of the battery that provides ionic conductivity, enabling Li+ ions to transfer between the two electrodes, while not being electronically conductive. There are two main types of electrolytes: liquid (aqueous electrolyte) and solid (Ceramic Electrolytes).

1) Aqueous Electrolytes:

Aqueous electrolytes may conceptually be safer and have lower potential environmental impacts, but the restricted electrochemical voltage window (1.23 V), limiting their use in Li-ion batteries, which means that by increasing the voltage over this value, there are unwanted side effects that will occur, such as the electrode reacting with water to produce free hydrogen. However, this issue could be solved using a “salt in water” electrolyte, where the concentration of salt increases the voltage range enabling the cell to work over high potentials [16].

2) Ceramic Electrolytes:

Recent advances in battery technology involve using ceramics as electrolytes, resulting in higher electrical conductivity. Working to improve the conductivity of ceramic electrolytes to yield materials with performance like that of liquid electrolytes continues, with some promising results [17].

iv. Separator

During discharge, Li+ ions are transmitted to the cathode by an electrolyte. The separator is meant to prevent a short circuit between the anode and cathode. There- fore, the safety performance, cycle life, and discharge rate of LIBs are highly dependent on the separator. Polyolefin ((CH2CHR)n, where R is an alkyl group) is widely used as a separator. This kind of separator has a high degree of stabilization, low cost, and appropriate pore size.

Generally, there are more intensive requirements for high- performance batteries such as high current and high-rate discharge, long-time stable output, high heat resistance, and low heat shrinkage. As a result, the separator becomes thinner, which increases the risk of thermal breakdown during high discharge rates, therefore, researchers are developing a new separator that can meet high performance requirements [18].

III. THE HEAT GENERATION SOURCES IN THE BATTERY

In order to design effective thermal management systems, it is important to state the sources of heat generation in Li- ion battery. Heat loss in the lithium-ion battery has two main sources: reversible and irreversible losses.

i. Reversible loss

In order to design effective thermal management systems, it is important to state the sources of heat generation in Li- ion battery. Heat loss in the lithium-ion battery has two main sources: reversible and irreversible losses.

ii. Irreversible Loss

The irreversible losses are due to ohmic heat generation that occurs due to the internal ohmic resistance of the battery. Ohmic heating in a battery is based on three different factors: material resistance, the movement of ions through the electrolyte, and the heat generated through the current collector. Ohmic heat generally can be calculated through the equation: $p = I^2R$, where I is the current output from the battery, and R is the internal resistance of the battery. Irreversible heat loss is a significant concern for lithium-ion batteries, as excessive heat generation can lead to reduced battery performance, shortened battery life, and even safety hazards such as thermal runaway. Therefore, it is crucial to use an effective heat management system to keep the temperature of the battery within the optimal range [19].

IV. THERMAL RUNAWAY

Thermal runaway is a dangerous challenge facing manufacturers while designing Li-ion batteries. Thermal runaway is an uncontrolled chain reaction that occurs inside the battery, causing an increase in temperature and internal pressure of the battery pack, leading to gas leakage, fire, and explosion [20]. Three main causes lead to thermal runaway: mechanical, electrical, and thermal reasons. In this review, we will discuss only thermal reasons, where they involve overheating, mainly due to poor thermal management [21]. At temperatures above 80○C, Solid Electrolyte Layer (SEI), which is the passivation layer formed on the electrodes by the electrolyte decomposition, begins to break down. When SEI is broken, carbon can react and reduce the electrolyte, forming an exothermic reaction that can occur at 110○C. Also, at a temperature above 100○C, the electrolyte begins to break down, and at a temperature above 135○C, the separator melts, then thermal runaway starts. Therefore, efficient thermal management system will prevent thermal runaway from occurrence, and thus increase the battery safety [22],[23].

V. TEMPERATURE EFFECT ON THE PERFORMANCE OF LI-ION BATTERIES

Thermal run away starts at temperatures more than 80◦C. Even at relatively low temperatures from 40◦C to 80◦C and less than 20◦C, there is a negative impact on the performance of the battery. Generally, there are two types of temperature effects that can harm the battery: Low and High-temperature effects [24].

i. Low-temperature effect

At low temperatures, the power and energy density de- creases. The power and energy densities of Panasonic 18650 LIBs were 800 W/L and 100 Wh/L at 25○C, and these values were reduced by 98.75% and 95% to < 10 W/L and 5 Wh/L at 40○C [24]. The state of charge of the battery is also affected. Another effect is lithium plating issues. At low temperatures, during the charging process, the ions become less mobile which decreases the diffusion rates of the ions in the anode. This leads to the accumulation of Lithium-ion on the surface of the anode, thus reducing the capacity of the battery. In addition, by decreasing the temperature, the viscosity of the electrolyte decreases. This increases the internal resistance of the battery, so the impedance of migration of the ion increases. Also, this plating exists in the form of dendrites, which may penetrate the separator, causing short circuits [25].

ii. High-temperature effect

High temperatures cause irreversible damage to the battery system. High temperature decreases the capacity of the battery by 38.9% at 70○C. In addition, at high temperatures, the impedance of the battery increases reducing the performance and increasing the rate of heat generation. At high temperatures, self-discharge increases, the state of charge of the battery (SoC) decreases and thermal stability also decreases [24].

VI. SINGLE HEAT MANAGEMENT SYSTEMS

Air-cooling is the simplest approach to managing the temperature inside the battery system. Due to the simple structure, low cost, ease of maintenance and lightweight, air cooling is widely. This system is adopted by many manufacturers, such as Chinese and Japanese EV manufacturers, and has been used in considerable EV models such as BYD E6, Toyota Prius, Nissan Leaf, etc. However, this system faces some issues related to the cooling capacity, and non-uniform temperature distribution. Generally, there are two main types of air-cooling system: passive and active cooling systems [26-27].

i. Passive air-cooling system

A passive system takes the air directly from the atmosphere or the cabin as shown in Fig. 2. In this system, the battery pack is placed in a location, where it can be exposed to the natural airflow. The battery pack is surrounded by fins or channels that can increase the surface area of heat transfer. As the car's speed increases, heat energy is dissipated into the environment. The advantage of this system is that it does not require any energy-consuming components such as fans, and pumps. In addition, this system is cost-effective and lightweight. However, this system has a low cooling capacity, affected by the ambient temperature and is not appreciated for high discharge rates[28].

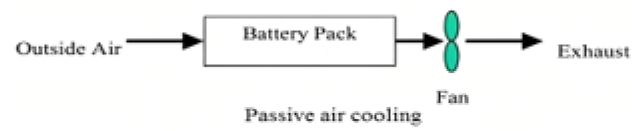


Figure 2 Passive cooling system diagram [27].

ii. Active air-cooling system.:

Due to the low heat capacity of the passive air-cooling system, manufactures have adopted the active cooling system. The active cooling system as shown in Fig. 3 is a type of cooling system that uses fans to force air to enter the battery pack. There are many modifications applied to this system related to the configuration of the battery cells. In the old series configuration, temperature of the coolant may rise significantly due to heat absorption when coolant flows past a series of cells, and this will lead to the cell temperature near the exit being higher than that near the inlet. This increases the temperature gradient through the cells of the battery system, thus reducing the battery life span and increasing the chance of the thermal runaway. The best configuration of the battery system is the parallel configuration. This configuration has been applied by Toyota's Prius hybrid for its battery system. The key to the efficiency of this system is the equal distribution of the coolant air among all cells of the battery. This configuration can reduce the temperature gradient between battery cells, and thus improve performance [28].

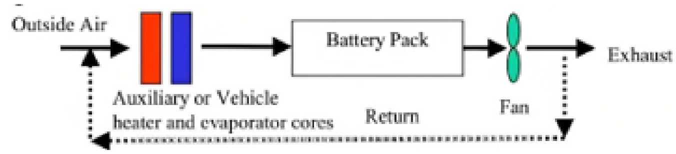


Figure 3 The active cooling system diagram [27]

VII. LIQUID COOLING SYSTEM

Air cooling systems may not be suitable for most high- performance electric vehicles, due to the limited heat capacity of air [29]. Compared with air, liquid has higher specific heat capacity and thermal conductivity. In other terms, liquid thermal management systems have higher performance than air cooling systems. Liquid cooling systems can be categorized into direct and indirect liquid cooling systems [30].

i. Indirect Liquid cooling systems:

In the indirect cooling system, the coolant is not in direct contact with the battery, instead, it is circulated through heat- conducting material such as cold plates, or tubes [31]. In this system, the coolant used can be water or ethylene glycol, which has a lower viscosity than oil or dielectric material, which would be discussed later. This results in lowering the energy requirement of the auxiliary parts [32]. The design of the system is designed as cooling plates in the middle of the battery cells as shown in

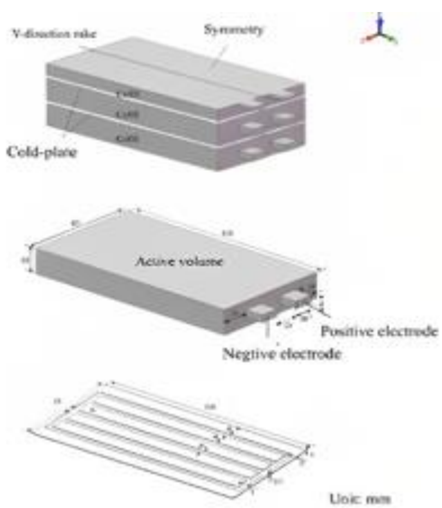


Figure 4 Deign of the indirect cooling system [33]

The physical dimension of the channel, such as its length, width, and route affect the performance of cooling plates. J. Zhao, et al [33] experimented to enhance the heat uniformity of this system. The results showed that the performance became better in two ways: shortening the flow paths by increasing the flow channels and increasing the contact area between the battery and the cooling channel. Y. Huo, et al [34] studied the effect of using mini-channel cooling plates. The results showed that the maximum temperature of the battery's pack was decreased. The temperature uniformity of the system became better by increasing the flow rate of the coolant. However, if the flow rate of the cooling liquid increased continuously, the impact degree became weaker, and the energy consumption of the pump increased. This was also supported by C. Lan, et al [35] who determined that increasing the flow rate from 1 L/min to 4 L/min, caused the pump power consumption to increase by 74 times. Further study is necessary to solve the problems of a direct cooling system: The viscosity of the cooling media should be optimized because it affects the energy consumption of the system and the weight of the battery pack. In addition, the coolant should exhibit excellent electrical insulation, flame limitation, and chemical stability. In general, the optimal design for the indirect cooling system required to decrease average temperature and increase temperature uniformity [35].

ii. Direct liquid cooling:

Unlike indirect cooling systems, the fluid used is electrically non-conductive, which enhances cooling efficiency of the system [36]. In this system, a dielectric liquid is circulated through battery cells [37]. A dielectric fluid is used as both a coolant and an insulator to replace some of the limitations of the solid insulation layers [38]. There are many studies carried out to analyze the efficiency of this system.

W. Wu, et al. [39] developed a battery module with 32 cells. They analyzed the effect of partial cooling by reducing the height of the fluid channel. This reduces the thermal behavior of the battery; however, this reduces the energy consumption of the auxiliary system. X. Tan, et al. [40] analyzed the effect of cell spacing on the system performance, using a battery module of 14 pouch- type cells of 20 Ah as a reference. Pouch-type battery is a type of cell with a high energy-to-mass ratio and packaging efficiency [41]. The results of the study demonstrated that cell temperatures and pressure drop of the system decrease by increasing cell spacing. However, the authors mentioned that in a practical application, the lowest cell spacing is preferred due to space limitations in electric vehicles. M. Larra naga Ezeiza, et al. [42] made a recent study to enhance the performance of Direct Liquid Cooling. The study was carried out on a large-scale lithium-ion 60 Ah (Nickel Manganese Cobalt) NMC pouch-type cell. The study also focused on comparing the different flow patterns, the thermal performance of the battery cell, the energy density of the system, and the power consumption. The results of the study showed that at flow rates, below 0.4 L/min, U-shape design, as shown in Fig. 5 improve the fluid dynamical aspect of the cooling, maintaining the heat homogeneity inside the battery without increasing the power

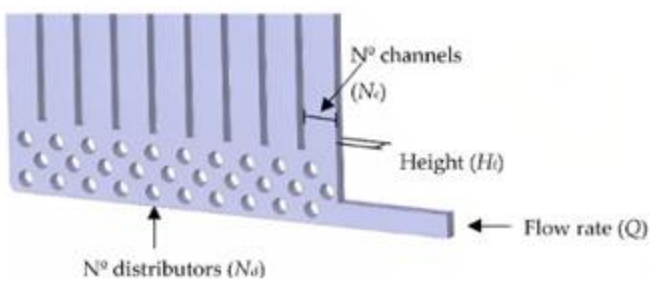
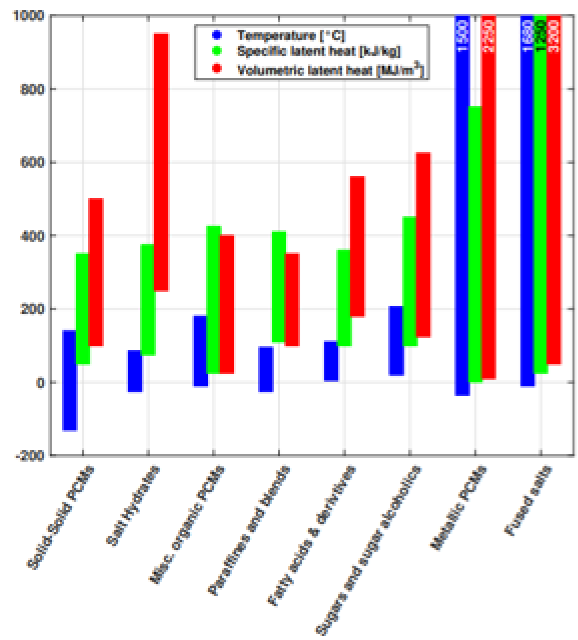


Figure 5 U-shaped Design for direct cooling system and parameters implemented in the optimization process [43]

consumption. Also, increasing the number of channels increases the power consumption of the system increases; however, this decreased the temperature difference between battery cells. The number of distributors increases the power consumption of the system and the thermal heterogeneity of the battery cell. However, a minimum number of components to distribute the inflow and outflow are necessary, thus avoiding hot spots in the system as shown in Fig. 6 [43].

VIII. Phase Change Materials (PCMs)

A phase-changing material is a material that can release or absorb adequate energy at phase change to supply useful heating or cooling effects [44]. Many different materials with different phase transitions can be used according to the desired transition temperatures, specific latent heat, and volumetric latent heat for different classes of PCM as shown in Fig. 7. At end of the phase change process, the material reaches the melting point. This means that it can cope with the thermal load of the battery without successive charge/discharge cycles [46]. In addition, this material has low thermal conductivity. An approach to solve the problem of low thermal conductivity is adding PCM directly in



contact with the batteries. There are also two Aluminium plates on the top and bottom of PCM to dissipate heat absorbed by PCMs as shown in Fig.8 . When the battery is charged or discharged, heat generated in the cells transferred to the PCM, which is in direct contact with the cells Although increasing the PCM mass can delay the time of phase change, this will not reduce the energy consumption, because it increases the weight and reduces EV performance. Therefore, the appropriate PCM mass must be determined [47]. Another important factor to be considered in the application of PCM to thermal management system is to select the appropriate PCM. The proper PCM should have characteristics of high latent heat, high heat capacity, high thermal conductivity, and phase change temperature within the operating range of the battery. Moreover, the PCM should be chemically stable and non-toxic with low or no sub-cooling effect in the freezing process [48]. Paraffin (C_nH_{2n+2}) is considered the most suitable PCM, but it has the disadvantage of low thermal conductivity [49]. Therefore, there have been many studies to improve the thermal conductivity of PCM without significantly affecting the good characteristics. There are three methods for improving the thermal conductivity of PCM: adding thermally conductive material such as carbon-nano powder, adding metal fins, and adding porous material such as an expanded graphite matrix (EGM). Despite efforts to improve the low thermal conductivity problem, PCM is still difficult to apply to automotive BTMS due to problems such as leakage, poor mechanical properties, and low surface heat transfer between the PCM and the external environment [50].

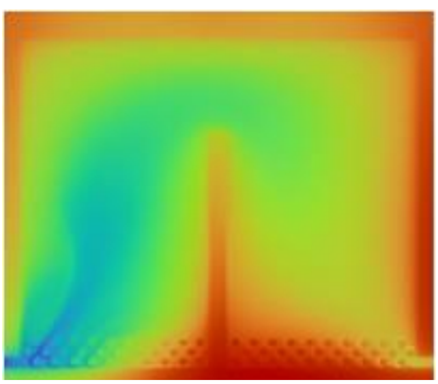


Figure 6 Thermal image of cooling design without channels [43]

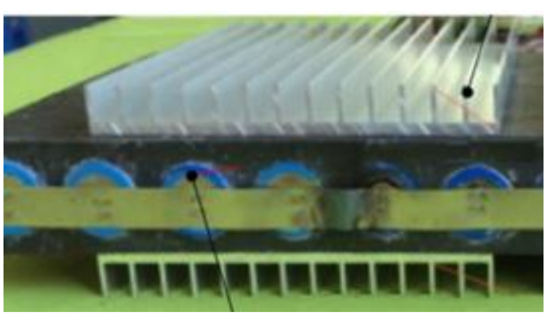


Figure 8 Small prototype of the BTMS consisting of LDPE/EG/paraffin composite PCM with battery cells and aluminum fins [47]

IX. Heat Pipes (HP)

A heat pipe is a material designed to operate spontaneously without external pumped power to transport large amounts of heat energy. It has many advantages: compact structure, flexible geometry, long lifetime, and low maintenance. However, the heat pipe is not yet applied to the main purpose of an actual electric vehicle's thermal management system, due to their low heat capacity and small contact area. This system is composed of three sections: an evaporator section, an adiabatic section, and a condenser section. Evaporator section is attached to a heat source or the battery cells, then the working fluid in a heat pipe evaporates by absorbing heat from the heat source. After that, the fluid moves from the evaporation section to the condenser section due to the difference in the internal pressure of the container in the adiabatic section. In the condenser section, the working fluid condenses through external heat exchange [51]. As said before, the surface area of contact between the heat pipes and the battery cell is limited, therefore the heat pipes need to be inserted into the cooling plate and has excellent thermal conductivity. When the battery is heated, the evaporator section of the heat pipe coupled with the cooling plate absorbs the heat of the battery through conduction and can be cooled through the outside air or liquid in the condenser section stretched to the end on the cooling plate as shown Fig. 9, 10. N. Lu, et al. [53] investigated the thermal behavior of Li-

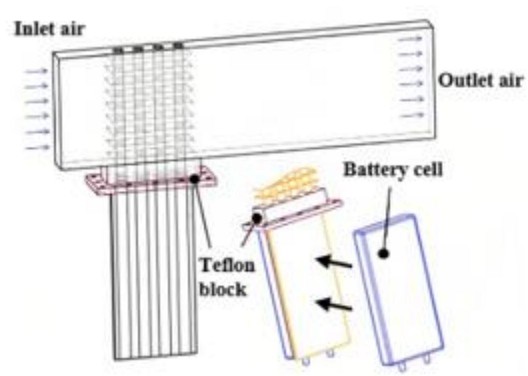


Figure 9 The condensation section of heat pipes cooled by air [52]

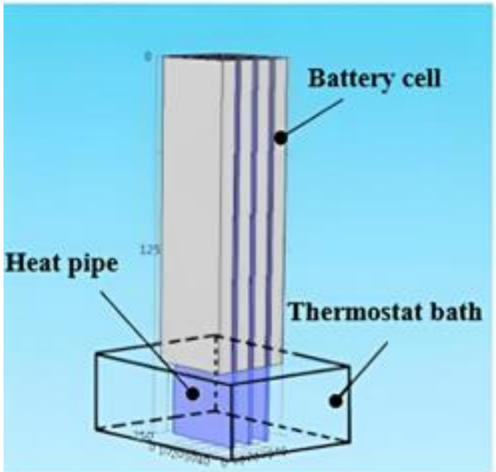


Figure 10 The condensation section of heat pipes cooled by liquid [52]

ion batteries with natural convection, forced convection, and heat pipe battery cooling systems by differentiating the state of charge and discharge current when discharging. They considered a heat pipe cooling system because forced convection cools more efficiently than natural convection, but temperature distribution is not uniform. T.-H. Tran, et al. [54] compared with the thermal performance of the cylindrical cells with a heat pipe cooling system and a natural/forced air convection cooling system and compared the thermal performance of the flat heat pipe cooling system by varying the positions. Results showed that heat pipes are 30% lower in thermal resistance with natural convection and 20% lower with forced convection when the air velocity is slow. Y. Ye, el al. [55] investigated the cooling performance of a heat pipe cooling system using an additional copper heat sink and cooling fins to quickly charge the Li-ion battery as shown Fig. 11. Simulation results of their system with forced air convection cooling emphasized that heat dissipation performance was improved with the aid of cooling fins, which enabled effective battery thermal management at the cell level, but not at the pack level. R. Zhao, et al. [56] compared the thermal behavior of Li- ion batteries using four different evaporator cooling types of heat pipe cooling systems under various conditions. According to the results of the study, the heat pipe cooling system with a combination of air cooling and wet cooling for cooling the condenser section of the heat pipe at the 3-C discharge rate was the best method with a temperature gradient of 1.2○C and

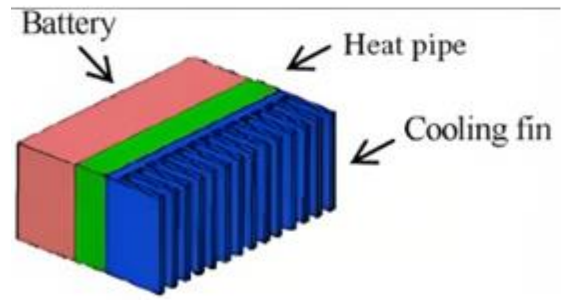


Figure 11 Fin design of the heat pipe system [57]

maximum temperature of 48○C.

X. A HYBRID THERMAL MANAGEMENT SYSTEM COMBINING PHASE CHANGE MATERIALS WITH FORCED-AIR COOLING

i. Mechanism

As discussed before, forced air convection cooling system can be effective for batteries with low charge/discharge rates. Also, this system faces a drawback of leakage of temperature homogeneity in battery cells, leading to different degradation rates between the cells. As a result, the whole lifetime of the battery would be shortened. Although using a new air duct design can enhance temperature homogeneity, it increases the complexity of the system [58]. The Phase change material (PCM) is a good solution for absorbing excessive amounts of heat at high charge/discharge rates, reducing the maximum temperature and temperature difference between the battery cells. However, it is found that the PCM can run out of the latent heat at a high rate of successive charge/discharge cycles. Researchers found that the efficiency of PCM material can be enhanced by combing another system, which is the forced induction cooling system [59]. Z. Ling, el al. [60] made an experiment to study the effect of combining forces and natural induction cooling systems on the maximum temperature and temperature between battery cells at different discharge rates of 1-C and 2-C.

ii. Performance

At 1-C discharge rate, the completely passive thermal management system (black lines) and the enhanced system that combines PCM with forced air convection (red lines) success- fully kept the battery temperature under 45○C in all five cycles. Peak temperature in each cycle was similar between the two thermal management systems, but maximum temperature at the end of a charge in the active system was lower than the completely passive system, as shown in Fig. 12. At 2-C discharge rate, the passive system could control battery temperature under 45○C in the first two cycles but failed at the third discharge, because the PCM ran out of

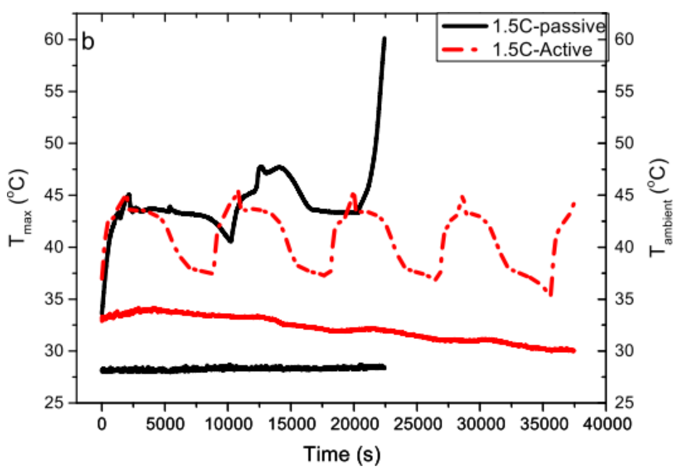


Fig. 12. Comparison of the maximum temperature in the battery pack between the passive air cooling and forced cooling system combined with PCM at discharge rate of 1-C [60]

latent heat and natural convection was not effective in dissipating heat energy from the PCM. On the other hand, the active system could control a temperature of less than 45○C throughout the five discharge cycles, as shown in Fig. 13. The temperature gradient at any discharge rate, whether using the natural or active system, was kept under 3○C. These results were achieved due to using high thermal conductivity material of RT44HC/EG.

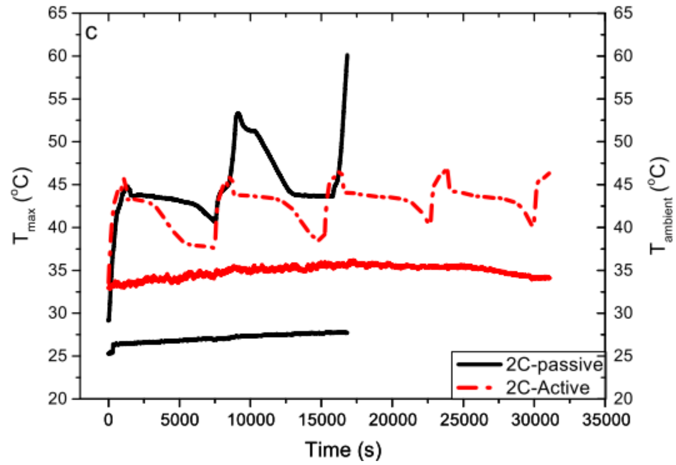


Figure 13 Comparison of the maximum temperature in the battery pack between the passive air cooling and forced cooling system combined with PCM at discharge rate of 2-C[59]

XI. A HYBRID THERMAL MANAGEMENT SYSTEM COMBINING PHASE CHANGE MATERIALS WITH HEAT PIPES

Another way to solve the problem of running latent heat from PCM is to increase the thermal conductivity of the PCM by combining it with Heat Pipe (HP). PCM has the advantage of keeping the temperature homogeneity. On the other hand, the heat pipe has high thermal conductivity which can lower the maximum temperature of the battery system. Z. Ling, et al. [60] studied the effect of combing the PCM with heat pipes on the maximum temperature difference and maximum temperature between battery cells. They structured the system to utilize the space between cylindrical cells, which means that the new system will not add much extra volume as shown in Fig. 14

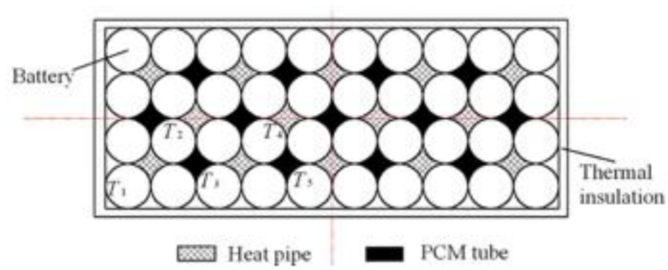


Figure 14 Schematic of hybrid battery system of heat pipes and PCM [60]

i. Mechanism

Heat pipes were made of aluminum, which has a low specific heat capacity of 900 J/Kg.K and high thermal conductivity of 235 W/m.k Therefore, it can increase the efficiency of heat dispassion. Heat pipes used were composed mainly of two sections: the condenser section and the evaporation section. In the evaporation section, the outer shape of the heat pipe is specially designed to have four circular arc surfaces, which enable assembling with four 18650-type battery cells. in this section, the working fluid can absorb the heat from the battery. In the condensation section, four fins are designed to increase the heat transfer area exposed to ambient air. In order to enhance the thermal conductivity of heat pipes, working fluid must be used. Acetone was the best choice. Ace- tone is chemically not reactive with aluminum and has high- temperature stability. In other terms, it does not decompose with temperature elevation [61]. An optimal charging ratio of 40% was used. The charging ratio is the ratio between the volume of the fluid to the total inner volume of the pipes. A too-small charging ratio can cause local dry areas inside heat pipes. On the other hand, a large charging ratio can cause the liquid to be pushed to the condensation section. The PCM tubes were made of aluminum with the same design as heat pipes without the fin structure of the condenser. PCM used is industrial grade paraffin. This is the best PCM material used on large scales as discussed before [60].

ii. Performance

The system could keep the maximum temperature of the battery pack at 31.6○C, 38.9○C, and 47.7○C during the 0.5- C, 1-C, and 2-C discharge rates respectively at the end of the discharge process (DoC $\approx$ 1). DoC is Depth of Discharge, which indicates the percentage of the battery that has been discharged relative to the overall battery capacity. Also, the temperature difference in the battery pack was about 2.5○C at the 2-C discharge process. The results also showed that at 0.5- C and 1-C discharge processes, the PCM only partially melts and during the 2-C discharge process the PCM completes melting [60].

iii. Summary

The heat dissipation process in this system is completely passive, which does not consume energy, but is limited by ambient air to dissipate the heat energy. Therefore, the system could be used on scooters and motorbikes without any further optimization. For high discharge process, the system cannot keep the temperature at the optimal range. This system can be enhanced though combining air induction cooling system.

XII. A HYBRID THERMAL MANAGEMENT SYSTEM COMBINING PHASE CHANGE MATERIALS, HEAT PIPES, AND LIQUID COOLING

Air-cooling system is simple and cost effective. However, the system has limited cooling capacity due to low thermal conductivity, specific heat capacity. The heat pipes must be combined with another cooling system to increase the heat dissipation. The liquid cooling system has high cooling capacity, but also limited by complexity and cost of production. N. Putra, et al. [62] studies the effect of combining these three systems in a hybrid system that can utilize the benefits of each system and compensate the drawbacks of them.

i. Mechanism

This hybrid thermal management system integrates flat heat pipes, air cooling, and water spray cooling, as shown in Fig. 15. In this system, micro heat pipe array (MHPA), which is a type of flat heat pipe with several microscale channels inside, enables high thermal conductivity and good temperature uniformity. Aluminum fins were attached to the cold end of the MHPA to increase cooling surface area. Water was pumped from a thermostatic water reservoir and then sprayed through a nozzle onto the fins. Air cooling was provided by adjustable cooling fan. The required cooling capacity could be achieved by heat pipes and forced air cooling at normal driving because the heat generation of the battery pack was small in this driving condition. As a result, the intermittent spraying only worked under the high load driving conditions.

ii. Performance

The experiment conducted to compare between using the heat pipe with heat cooling at different air velocities. The research focused on different driving conditions, but we will focus only on the constant discharge process of 1-C, 2-C and 3-C. The proposed hybrid system could keep the maximum temperature of battery at 28.6○C, 32.1○C, and 35.1○C throughout charge/discharge cycles at discharge of 1-C, 2-C, and 3-C respectively, while the heat pipes forced air induction system with different velocities at temperature below 34○C , 39○C. 45○C at discharge rates of 1-C, 2-C, and 3-C respectively as shown in Fig. 18 . The temperature difference for hybrid system was below 1.2○C ,2.3○C, and 3○C discharge of 1-C, 2-C, and 3-C respectively, while the heat pipes with forced air induction system was below 4○C, 6.1○C, and 6.8○C, discharge of 1-C, 2-C, and 3-C respectively.

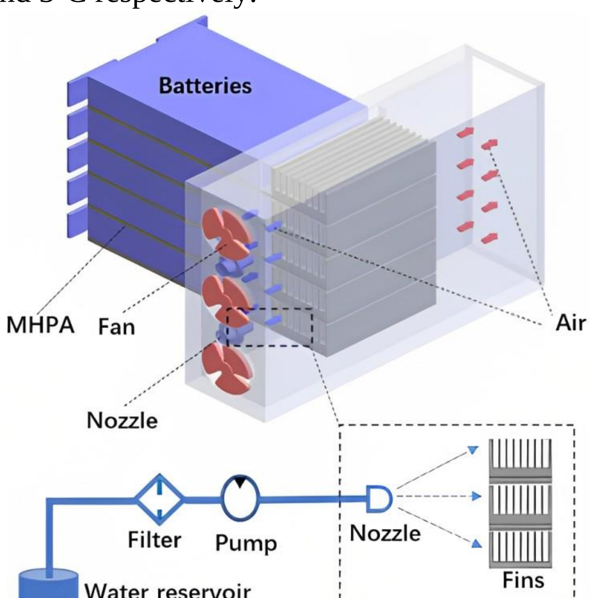


Figure 15 Schematic of the Hybrid system combining phase change materials, heat pipes, and liquid cooling [62].

iii. Summary

The heat dissipation process in this system is completely passive, which does not consume energy, but is limited by ambient air to dissipate the heat energy. Therefore, the system could be used on scooters and motorbikes without any further optimization. For high discharge process, the system cannot keep the temperature at the optimal range. This system can be enhanced though combining air induction cooling system.

XIII. A HYBRID THERMAL MANAGEMENT SYSTEM COMBINING PCM AND LIQUID COOLING SYSTEM

One modification to PCM is by combining a liquid cooling system. Q. L. Yue, et al. [63] studied performance of the hybrid system of PCM and water-cooling system in four different configurations.

A. Mechanism

The study focused on four configurations of the system for the investigation: -

1) Parallel configuration, where there are two parallel ways for heat dissipation from battery cells: one to the PCM

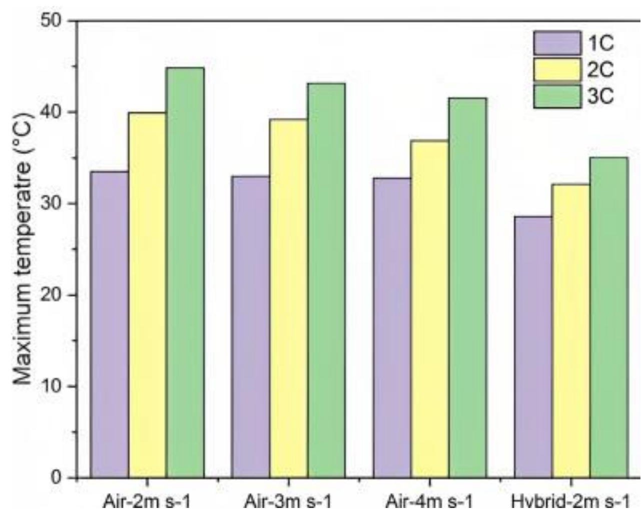


Figure 16 . The maximum battery temperature comparison of 2, 3 and, 4 m/s PCM combined with air cooling and hybrid system combining phase change materials, heat pipes, and liquid cooling at different charge process of 1-C,2-C, and 3-C [62].

and one to the water-cooling channel. In other terms, each battery is being cooled by two methods: PCM and water cooling at the same instant as shown in Fig 17,(a)

2)Series-1 configuration, where one cell is adjacent

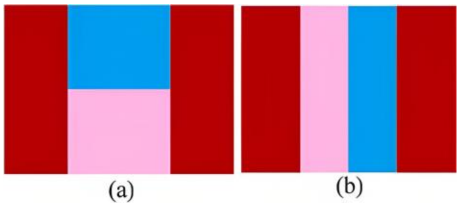


Figure 17 Fig. 17. Schematic of the configurations: (a) parallel, and (b) series-1. Red, light pink and blue colors represent cells, PCM and cooling water, respectively [63].

to the PCM, and the other is adjacent to the water-cooling channel, where PCM is used to cool a cell and liquid cooling is used to cool the other cell. as shown in Fig. 17 (b).

3) Series-2 configuration, where both cells are adjacent to the PCM, and the water-cooling channel is sandwiched between them, where the PCM is exposed to cool the cells and water cooling is used to cool the PCM as shown in Fig. 18 (a).

4) Parallel/series configuration is a combination of both parallel and series configurations, as shown in Fig. 18,(b), where X configuration is applied. Each adjacent cell is cooled by two methods. The difference between this configuration and the parallel configuration is that in the parallel configuration, the upper part of the two adjacent batteries is cooled through water cooling and the lower part is cooled through PCM, while in Parallel/Series configuration the upper and lower parts of the two batteries are being cooled through PCM and liquid cooling.

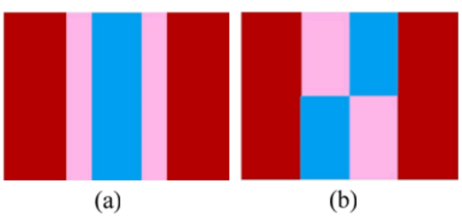


Figure 18. Schematic of the configurations: (a) series-2 and (b) parallel/series. light, pink and blue colors represent cells, PCM and cooling water, respectively[63].

ii. **Performance**

1) In parallel configuration, the maximum surface temper- ature of the cells is 52○C. The maximum surface tem- perature difference is not less than 9○C. These results showed the poor performance of this configuration in creating a uniform temperature distribution between the cells. Also, this configuration is not appropriate for high- performance use.
2) In Series-1 configuration, the PCM was completely melted at 125 s, and the maximum surface temperature was 51○C for both cells. The maximum temperature difference of about 6○C and after the melting process of the PCM, decreased to 3○C. The PCM thickness in this configuration is half of the PCM thickness in other configurations, and consequently, the PCM melting process occurred faster.
3) Series-2 configuration: - In this configuration, the PCM was completely melted at 125 s, and the maximum surface temperature was 51○C for both cells. The maxi- mum temperature difference of about 6○C and after the melting process of the PCM, decreased to 3○C. The PCM thickness in this configuration is half of the PCM thickness in other configurations, and consequently, the PCM melting process occurred faster.
4) Parallel/series configuration: - The PCM melted at 236 s and the maximum surface temperature was 47○C. This performance showed poor performance in terms of temperature difference because each cell was in direct contact with both PCM and cooling water, which both had different temperatures.

iii. Summary

Series configurations are better at creating uniform temperature differences in battery cells. The parallel/series configuration shows the best performance for 400 s operation of the cells. The series configurations, particularly, the series-2 configuration can provide a better performance. For instance, when the heat dissipation rate is not too much, the series configurations are more effective. However, for larger dissipation rates, parallel/series configurations are more suitable.

In practical applications, further efforts in terms of parametric study and optimization must be performed.

XIV. A HYBRID THERMAL MANAGEMENT SYSTEM COMBINING HEAT PIPES, CSGP, AND FORCED INDUCTION COOLING SYSTEM

Another promising hybrid thermal management system was studied by G. R. Molaeimanesh, et al [64]. The authors of this research enhanced the thermal conductivity of heat pipes by combining them with a composite silica gel plate (CSGP). Also, they studied the effect of combing other forced induction cooling systems such as liquid and air-cooling systems to enhance the cooling capacity.

i. Mechanism

CSGP is manufactured by adding expanded graphite (EG) with high thermal conductivity added into silica gel (SG) to increase the thermal conductivity of EG-SG. After that, the copper foam was employed to form CSGP. CSGP was used directly in the module as shown in Fig. 19. The forced air convection module with CSGP as shown in Fig. 20 has a fin structure to increase the area of heat transfer and increase the rate of heat dissipation compared with other systems proposed. The liquid cooling module with CSGP, as shown in Fig. 21 transfers the heat generated by batteries to the CSGP. CSGP then transfers the heat through the water in copper tubes. Water in the tank continues to cycle for achieving the desired performance.

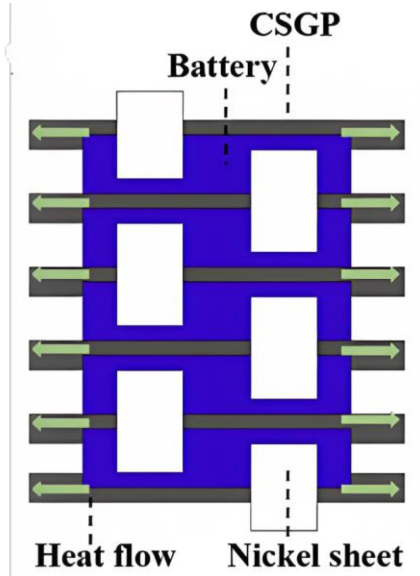


Figure 19. Schematic of the CSGP battery module [64].

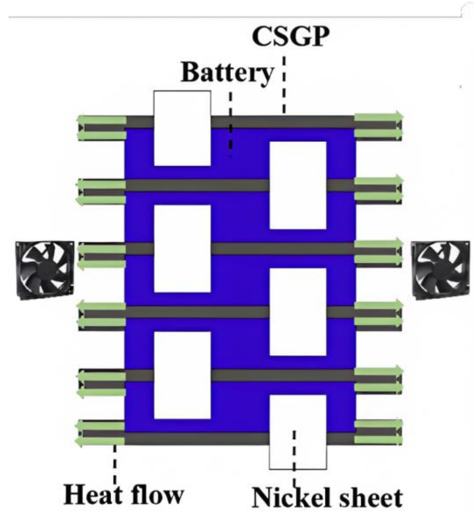


Figure 20 Schematic of the CSGP - forced induction battery module [64].

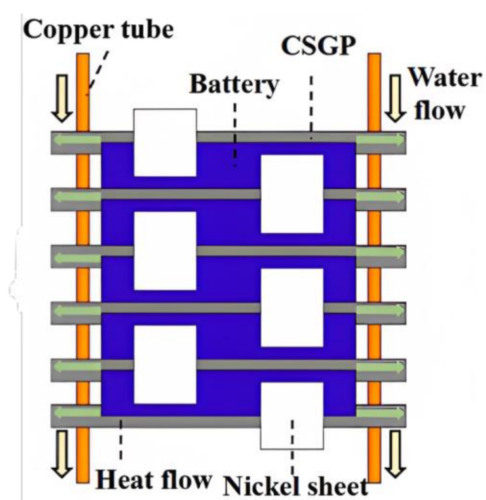


Figure 21 Schematic of the CSGP - Liquid cooling battery module [64].

ii. Performance

At a 4C discharge rate, the maximum temperature of the cells adhered to CSGP, battery after ten charge/discharge cycles is 64.3○C and the temperature difference in the cells is 6.7○C. These results are above the optimal range of the batteries. While, Battery cells with CSGP and forced air induction showed maximum temperatures of 51.8 °C, 51.2 °C, 49.8 °C and temperature differences of 2.1○C, 2.9○C, and 1.8○C at 3 m/s, 6 m/s, and 9 m/s air flow, respectively. Furthermore, battery cells with CSGP, heat pipes, and forced liquid induction showed maximum temperatures of 43.5○C, 43○C, and 42.7○C and maximum temperature differences of 3○C, 2.9○C, and 2.7○C at water velocities of 0.2 m/sec, 0.5m/sec, and 0.8 m/sec.

iii. Summary

With the EG and copper foam addition, the thermal conductivity of CSGP has been greatly enhanced. Besides, the water flowing in copper tubes can carry out hybrid cooling through the water tank for improving the cooling effect further. The results show that liquid cooling systems with CSGP and hybrid cooling strategy for battery modules exhibit superior controlling and balancing temperature performance, especially at high discharge rates. Overall, this system can be installed in daily-use electric cars without any further optimization.

XV. Conclusions

In conclusion, this review analyzed the main structures of lithium-ion batteries and highlighted the sources of heat generation within them, emphasizing the impact of temperature on battery performance and safety. The review further explored single thermal management systems like heat pipes, air cooling systems, liquid cooling systems, and Phase Change Materials (PCMs) to address their drawbacks. Heat pipes were found to have low heat capacity, air cooling systems had low cooling capacity, liquid cooling systems exhibited low thermal conductivity, and PCMs faced challenges with both thermal conductivity and performance in successive high rate of charge/discharge cycles. Combining one or more of these technologies in a hybrid configuration has become recognized as an effective solution for these problems. Among the various hybrid systems discussed, the combination of heat pipes, com- posite silica gel plate (CSGP), and liquid cooling demonstrated high performance at a discharge rate of 4-C. This particular system successfully maintained maximum temperatures below 43.5○C and maximum temperature differences below 3.5○C, with water velocity of 0.2 m/sec. In contrast, other hybrid thermal management systems fell short of achieving the de- sired performance at such high discharge rates. Therefore, it will be critical to carry out more research in the near future on integrating various heat management systems to handle the demanding needs of lithium-ion batteries. By exploring and developing hybrid approaches, researchers can overcome the limitations of individual systems and pave the way for enhanced battery performance, extended lifespan, and im- proved safety. These developments will surely help lithium-ion batteries become more widely accepted and used in a variety of applications, including consumer electronics, electric vehicles, and renewable energy storage systems.

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