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Cooling Strategies of Lithium-Ion Battery Pack - A Review

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Abstract

Lithium-ion batteries' physical properties classify them as one of the most important sources of clean energy that overcome the need for fuel usage. The rated operating temperature and its uniformity are of the main demands of Lithium-ion batteries. In this survey, several types of studies have been reviewed with the aim of understanding the thermal management systems used to control the temperature of lithium-ion batteries and their uniformity in the battery pack. They are represented by active and passive systems, as well as the hybrid system, which integrates each of the two mentioned systems into a system to obtain the best thermal performance. Active cooling systems were classified due to the type pf coolant used to air and liquid system, meanwhile passive system classified to PCM and heat pipe system. The survey reveals that the air-cooling of lithium-ion battery pack is better than the use of liquids. About 74% of the reviewed works prefer the use of active strategies. The working temperature under normal conditions should be within -20 to 60 °C, meanwhile the optimum range is 15 to 35 °C. The maximum temperature difference between batteries in the pack is preferred to be 5 °C or less.

Keywords: Lithium-ion battery, Cooling systems, Temperature uniformity, Passive and active cooling.

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1. Introduction

Thermal management systems in lithium batteries are critical components, which indicated the efficiency, and performance of battery packs by managing generation heat and temperature uniformity. Importance of thermal management systems motivated researchers to create new and effective methods to improve these systems. Because of this, there are now numerous methods used to cool battery packs, which are represented by external and internal systems. The first is by using various cooling fluids, such as liquids and air, and the second is by using phase change materials. In this survey, the focus will be on research related to the heat generated, the unregulated temperature distribution, and the systems used to control them, such as active and passive cooling systems.

2. Lithium-ion batteries design conditions

As previously stated, the generation heat and temperature uniformity in lithium battery are significant aspects that must be considered and managed due to their effect on batteries and may lead to thermal runaway. That is what Feng et al. [1] (2014) found in an experimental investigation of 25 Ah prismatic lithium-ion battery, where thermal runaway was practically analysed by measuring the internal temperature and temperature difference during thermal runaway process, the results showed that these phenomena occurred at 870 °C, 520 °C internal temperature and temperature difference receptivity. Many studies have been conducted to verify the temperature range at which lithium batteries can maintain their efficiency, performance, and life span. Due to a study conducted by Pesaran et al. [2] (2013), the acceptable working range of temperature is -20 to 60 °C under normal conditions, meanwhile the optimum working temperature range is 15 to 35 °C. Any increment in this range causes thermal issues, which result in result in capacity losses in lithium batteries. Battery lifespan is significantly impacted by temperature, as shown by a study conducted by Motloch et al. [3] (2002) that discovered increasing temperature by 1 °C in the operational range of 30 to 40 ° C reduces battery life by 2 months.

The battery pack is made up of a group of batteries that generate heat during the charge/discharge process; thus, temperature uniformity between batteries must be considered; anything other than that leads to a deterioration in performance in the battery pack. It was established by a study of Pesaran et al. [4] (2002), that it is preferable for batteries to have a temperature difference of 5 °C or less.

3. Types of cooling systems

Following the published works of researchers, it is critical to use appropriate lithium battery thermal management systems with a design compatible with the type of application. The following are the most significant cooling systems observed by researchers:

3.1. Air cooling system

Liu et al. [5] (2014) proposed a simple CFD module, as shown in Fig. 1, to determine thermal behavior and coolant flow profile in large parallel airflow-cooled battery pack. Some modifications to the original design of the module had been conducted, including controlling the tilt of the plates, the space between the packs and plates, and the distance between one pack and another. Despite the fact that coolant was distributed using wedge-shaped plenums, the distribution of coolant flowing inside cooling channels was found to be random, which leads to a reduction in temperature uniformity

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in the batteries and packs. These elements were modified individually to keep maximum temperature between cells lower than 5 °C. Velocity and temperate field in model may be simply determined using this approach, which can also be used to swiftly analyses or design a battery pack.

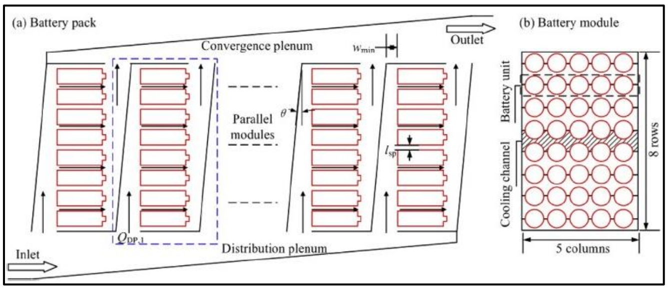

Fig. 1 (a) The schematic of a nested air-cooling system in a battery pack, in which the arrows indicate the airflow directions. (b) The arrangement of battery cells in a battery module.

Xu et al. [6] (2013) specialized in investigating the effect of forced air cooling on rate of heat dissipation in the battery packs. They discovered through the study that the axial location of battery packs relative to air flow direction directly influences the heat dissipation in the batteries, as placing the battery packs in a horizontal direction with the airflow is more effective than placing the battery packs in a longitudinal direction as shown in Fig. 2. Heat dissipation performance improved significantly when a U-shaped air duct at the bottom of the battery pack was used instead of an I-shaped air duct. Because of shortening the airflow path, increasing the thermal contact area by adding a bottom duct, and allowing natural convection to occur in the battery pack top area, it might increase the performance of heat dissipation.

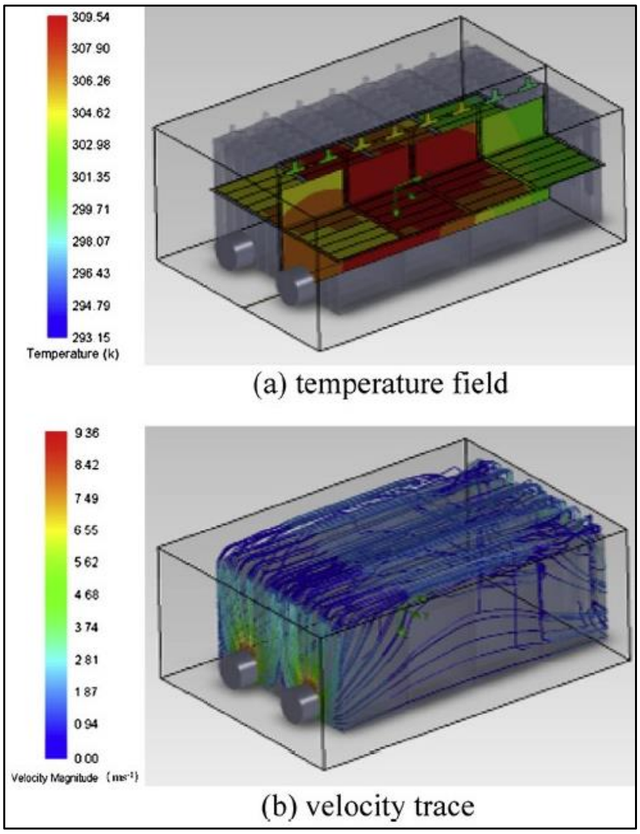

Fig. 2 The temperature field and velocity trace of longitudinal battery pack at 20 ºC.

Wang et al. [7] (2015) employed CFD to calculate three-dimensional 5x5 batteries, unsteady state thermal models and empirical heat generation source model for investigate thermal behaviors of cylindrical batteries undergoing discharge processes either with or without air cooling. One of most important results is that the maximum temperature ranges in which air cooling required was 20 to 35 °C and the different of temperature between the coolant and the cells depends on the cooling system's performance. In case ambient temperature over 35 °C, coolant at flow of 1 m/s necessary for maintain system performance; when the ambient temperature is below 20 °C, cooing become unnecessary; if discharging rate of batteries was 3 ºC or less, no active cooling required. If the discharge rate exceeds 3 ºC, active cooling required at temperatures of 20 °C or lower.

Du et al. [8] (2021) used 2D model combined with 3D CFD for describe generated heat and temperature distribution in the lithium batteries to study the effect of the geometric configuration cell within model on the performance of cooling system. They studied the effect of four battery arrangements on the cooling system, including a square arrangement, a staggered arrangement, and two trapezoidal arrangements cells temperate distribution. It turned out that square arrangement is an effective strategy to cool the cell, especially when the cold air intake is from the top of the batteries.

Ruhani et al. [9] (2021) conducted a numerical study of a two-dimensional, steady state air cooling system consisting of a battery pack with nine lithium batteries, investigating the influence of air flow rate and intake and outlet sizes on cooling system. The rate of air entering the cooling system, measured by a non-dimensional parameter (Reynolds number), ranges from 80 to 140, while the inlet outlet sizes range from 0.1 to 0.2. The temperature was calculated for each battery individually, different pressure and system temperature. It was shown that increasing Reynolds number minimize cells maximum temperature, an increase in air intake section and Reynolds number improves system pressure difference; module's minimum and maximum temperatures are at the air inlet and outlet, respectively.

Karimi et al. [9] (2021) investigated the experimental and numerical study of active cooling system designed to control temperature of a model with a 10-cell battery pack as shown in Fig. 4. Experimental results were compared with 3D thermal model simulation to validate the results. Effect of coolant velocities, fans position fans at inlet and outlet, the space between batteries, whether it was even or not, and the tilting of the model at different angles. They deduced that the use of high air velocity and a consistent space between the cells was proven to reduce the maximum temperature and temperature uniformity in lithium cells. Maximum temperature and uniformity are lowered with amount 2% and 3%, respectively, when batteries are tilted at an angle of 90º parallel to the air flow direction, and any increase in the spaces between cells results to a fall in the maximum temperatures.

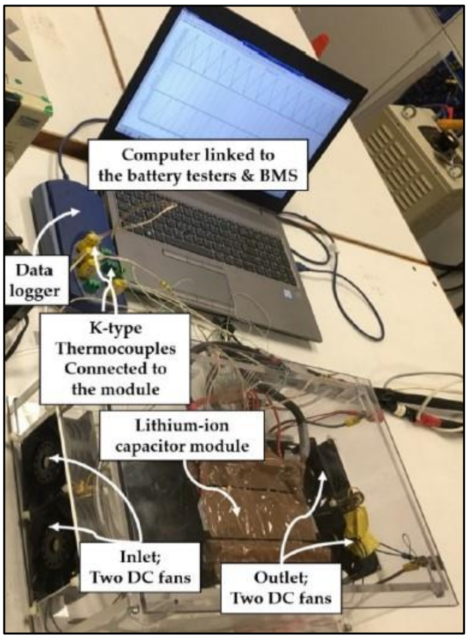

Fig. 3 Active cooling system experimental test bench for the lithium-ion battery module.

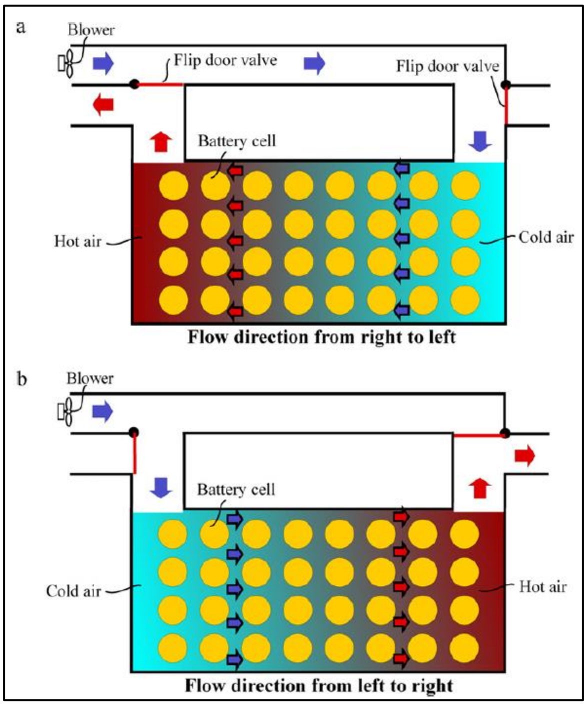

Fig. 4 Reciprocating air flow cooling system with various flowing direction (a) from right to left side and (b) from left to right side.

Mahamud et al. [10] (2011) developed modern cooling systems for lithium-ion cells that is numerically based on a 2D CFD model as shown in Fig. 4. A lumped-capacitance thermal model for cells and a flow network model were adopted. The computational fluid dynamics model's numerical results were validated by comparing them to an experimental study of an asymptotic model. The numerical study concluded that employing a reciprocating cooling system maximum temperature and temperature difference of cells pack by 1.5 ºC and 4 ºC, respectively, during of 120 s, when compared to a unidirectional flow cooling system during a period t = ∞ s.

Fan et al. [11] (2013) conducted a numerical study of a three-dimensional, unsteady state active thermal management system designed manage temperature of prismatic battery pack using computational fluid dynamics model. The cooling system uses air that passes through ducts with equal space on both sides lithium-ion cells. Effectiveness of gap spacing and cooling fluid velocity on cooling batteries packs has been studied. It was found that reducing gap and increasing coolant velocity decrease cells high temperature. The gap plays important role in determining temperature uniformity of batteries pack. After analyzing the current model, it was observed that using 3 mm spacing between cells with 40.8 m^3/h air discharge be an optimum option which meets the requirements of fan power consuming, maximum temperature rise, and temperature uniformity. The findings cooling in one side model is less efficient than cooling by two side. Uneven gap spacing has an effect on temperature distributions but little on maximum temperature rise.

Park et al. [12] (2013) used numerical simulation and air as a coolant; they theoretically developed a way to regulate heat in a battery pack to satisfy the essential thermal parameters (Fig. 6). The most important factor influencing performance was coolant uniformity inside radiator channel, which removed heat generated inside batteries. It has been demonstrated that optimum cooling performance may be accomplished utilizing pressure relief and tapered manifold ventilation without affecting the design of battery system. To optimize the cooling Performance, a theoretical study is also carried out as a design guideline.

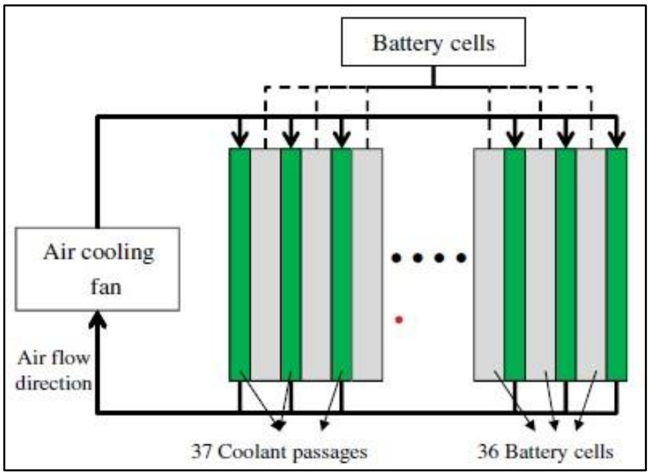

Fig. 5 Schematic diagram of battery system integrated with air coolant passages.

Xun et al. [13] (2013) designed a simulation analysis and an analytical model for the thermal management of lithium-ion battery packs in order to study the thermal behaviors of flat-plate and cylindrical battery packs during the discharging process. It was discovered that adjusting the channel size and number resulted in identical average battery temperatures for the same volume ratio of cooling channel and battery in a flat-plate design, although increasing the channel size increases cooling efficiency but leads to more uneven temperature distribution, and vice versa. As the Reynolds number of the cooling air is approximately 2000 or higher with a high discharging rate of 2 ºC, the volume ratio of the cooling channel to the battery has to be greater than 0.014 for flat-plate configuration.

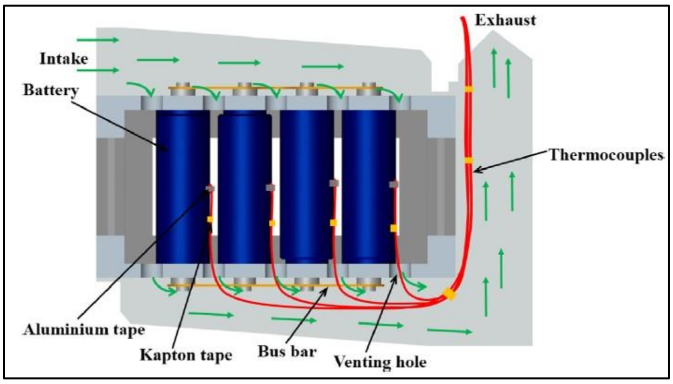

Fig. 6 Cross section view (left side view) of battery pack with thermocouple location on batteries and direction of air flow.

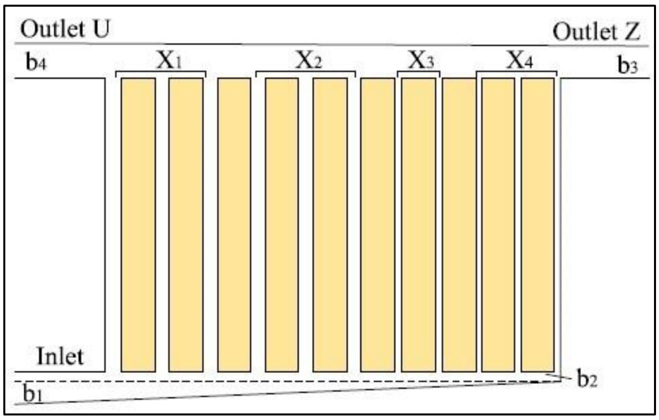

Fig. 7 The second stage optimization of J-type cooling system.

The cylindrical battery stacks examined in this research are typically less compact and more energy-efficient in cooling than the flat-plate battery pack and their basic thermal characteristics are comparable. Thermal management may also benefit from a counter-flow configuration of the cooling channels or from altering the flow direction of the co-flow system on a regular basis.

Saw et al. [14] (2016) used computational fluid dynamics research to study the air thermal management system designed for 38,120 Lithium-ion cells. The pack was made up of 24 batteries, copper bus bars, inlet and outflow plenums, and venting plates as shown in Fig. 6. The heat generated inside battery during the charging process was measured. Lithium-ion cells thermal efficiency was studied utilizing steady state modelling at different coolant mass flow rates. The numerical simulation results were used to predict and compare the relationship between Nu and Re with literature. To validate the relationship, the battery pack is also put through an experimental test at various charging rates.

Chen et al. [15] (2017) evaluated the influence of batteries configuration inside parallel air-cooled cooling system, as well as optimum level by configuring the space between batteries for improved cooling performance. Numerical models had been used to compute flow rates inside cooling channels, loses due to flow resistance and temperature inside battery. An optimization strategy was provided using these models for improve batteries configuration under constant conditions of battery heat generation. Results showed that maximum temperature difference was decreased by 42% and maximum temperature was reduced slightly due to cooling system modify, with no increase in system pressure drop.

Wang et al. [16] (2021) investigated improvement rate in cooling system efficiency by using parallel plates, which might vary airflow distribution inside model. They investigated various parameters that affected on cooling performance, like the plate number and the plate dimension, such as length and height. Within the acceptable range of power consumption loss, two parallel plates model shows the best cooling efficiency, maximum and different temperatures are reduced by 2.42 K and 3.46 K, respectively. Parallel plate length and height influence were investigated; the best length and height values were 1.5 and 30 mm, respectively.

Peng et al. [17] (2020) investigated experimentally optimum thermal management system used air as coolant designed for cylindrical lithium-ion cells. To validate the results, a single battery's heat dissipation performance was examined and compared to simulation results induced by a CFD model. Various battery configurations, different locations of the coolant entering and leaving and numbers were compared. The findings indicated that a configuration with a less length/width ratio was preferable to enhance performance. Cooling system's inlet and outlet arrangement, which enabled coolant flow across entirety of battery pack over relatively short distances, was more efficient cooling system. A design with several inlets and outlets can provide more flexible fluid flow state control and can significantly slow down battery heating.

Wang et al. [18] (2014) studied battery module thermal performance numerically using three-dimensional CFD method and single battery lumped model, which consist of different sizes like rectangular configurations with number 1 × 24, 3 × 8, hexagonal configuration 5 × 5, 19 and circular configuration with 28 cells, these approaches were examined when setting fans at various regions model in order to enhance temperature uniformity. The desirable configuration in terms of various factors like cost and cooling performance depending on results was cubic arrangement, while hexagonal configuration was ideal in terms of battery module space utilization. If fan positioned on top of the module, cooling performance was optimal.

Shahid et al. [19] (2018) studied experimentally cooling systems that improved temperature uniformity in battery pack. Air inlet plenum was added as supporter inlet for adjusted airflow direction, avoid recirculation and air reduction between batteries. Three alternative designs are investigated to study effects of intake plenum and battery direction. Module was carefully simulated using computational fluid dynamics, and the findings were validated using one battery experimental data. The results showed that battery average maximum temperature was reduced by 4% and the temperature uniformity was enhanced by 39%.

Liu et al. [20] (2019) designed a unique J-type air cooling system combining the U-type and Z-type designs. Using a recently founded battery model, a comparative geometrical investigation of significant design characteristics and theoretically ideal structures was initially carried out. Results demonstrated that high temperature was reduced by 35.3%, 46.6%, and 31.18% for U, Z, and J-type, respectively. The advantages and disadvantages of the J-type structure were investigated further by comparing it to the ideal U and Z-type designs. To show how the optimum settings for the air-based cooling system vary depending on the working conditions and how the J-type structure may be flexibly configured to meet the cooling requirement, a further J-type optimization with regard to the manifold design is also done as shown in Fig. 7. The modelling and optimization findings are validated by corresponding experiments.

Na et al. [21] (2018) developed reversed layered air thermal management system structure to enhance temperature uniformity in battery pack by dividing cooling domain into two portions, each with an air intake and an air exit. Cooling air flows in the opposite direction in the neighboring channels, exchanging heat through the transverse dividers. Three-dimensional computational fluid dynamics was used to compare reverse-layered airflow to unidirectional airflow. The study observed that reverse layered airflow cells maximum temperature and maximum average temperature differential more than unidirectional air flow.

Zhou et al. [22] (2018) conducted 3D-computational fluid dynamics model of cooling system for cylindrical lithium cells module based on air distribution pipes. The experimental tests validate the battery numerical module. Battery pack thermal properties and air flow field were investigated using numerical simulations at various discharge rates, orifice parameters impact and intake pressure on cooling approaches performance were investigated. Results revealed that increasing the intake pressure significantly reduced maximum temperature, resulting in considerable increase in power consumption. Meanwhile, it decreases as the orifice diameter and number of rows grow after a modest increase in power consumption.

Jilte et al. [23] (2018) conducted numerical investigation of transient conditions of new confined flow battery module operated under different discharge rates (6.94 ºC, 11.11 ºC). Typical standard flow battery modules were adjusted to include managed or directed airflow inside batteries in order to reduce the maximum and different temperatures in the module. Due to comparisons between cells based on three-dimensional transient CFD developed for a typical standard flow module and confined flow module, the second module showed surface temperature reduction and more uniform battery temperature when compared with first module.

Yang et al. [24] (2015) conducted a numerical analysis by developing thermal model for the battery pack and comparing thermal performances on various configurations of cylindrical cells for a LiFePO4 battery pack. The model validation tests are carried out on a single cell of the battery pack with a forced-air cooling system. The effects of longitudinal and transverse spacing on cooling performance for battery packs with aligned and staggered arrays are investigated. Under a constant flow rate of cooling air, the maximum temperature rise for staggered arrays is proportional to the longitudinal gap, whereas it is inverse for aligned arrays. For both aligned and staggered setups, increasing the transverse interval causes the battery temperature to rise.

3.2. Liquid cooling system

Liquid cooling systems have been considered one of the most essential systems that lead to a noticeable improvement in batteries pack performance, because of a reduction in the maximum temperature and uniformity of the batteries.

Chao et al. [25] (2021) studied battery pack cooling utilizing liquid cooling system with a main channel and sub-channels, as well as CFD simulations to investigate the impact liquid flow rate with temperature on cooling system performance as shown in Fig. 8. It discovered when increased the coolant flow rate reduced maximum temperature of batteries as well as the maximum temperature difference. Reduced coolant temperature causes a reduction in maximum temperature but increase in maximum temperature difference, resulting in an uneven temperature distribution.

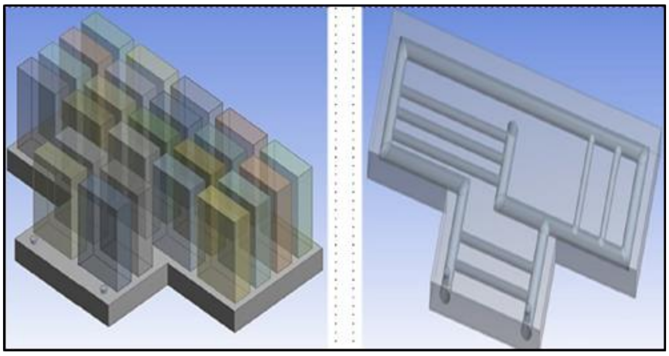

Fig. 8 The three-dimensional model of the battery cooling system and the structure of a cooling channel in a cooling plate.

Dilbaz et al. [26] (2022) used water and a hybrid nanofluid made of nanodiamond Fe_3O_4 water and ethylene glycol (ND-Fe_3O_4 W/EG) to improve heat dissipation rate for 20 AH rectangle-type battery pack. The cooling system employed five to twenty-five fins, different Reynolds number ranges from 100 to 800, various discharge rate 3 ºC, 4 ºC and 5 ºC and range 0 to 2% of nanoparticles of fraction volume. Results showed increasing Reynolds number and nanoparticle volume ratio led to decreasing temperature rising and optimizing the distribution in pack. Performance is improved by using more fins. When comparing the 25-fin configuration to the 5-fin model, temperature difference was reduced by 13.8%.

Jin et al. [27] (2013) improved performance with low-pressure loss by arranging angled slices over the horizontal fins of a traditional straight channel design. These angled slices form an angled fin array across the straight fins. These basic angled fins with optimized angles and widths were combined with liquid cooling plate. The boundary layers were re-initialized as result of this segmentation of the straight fin into angled slices, thereby lowering temperature rise due boundary layer thickness in fully develop region. The experiments data demonstrated that the oblique minichannel has greater heat transfer coefficients than the traditional straight minichannel. At 1.240 kW load and 54 m/s flow velocity or less, current system can maintain average temperature lower than 50 ºC.

Many studies compared air and liquid coolants to indicate which was more effective, showing the advantages and disadvantages of each under various conditions.

Chen et al. [28] (2015) examined four thermal management systems included air, indirect, direct liquid and fin thermal management systems. A typical pouch cells designed for electric cars was employed for assess the effectiveness of different strategies in terms of power consuming, maximum temperature, uniformity within cells and extra weight required. Results showed an indirect liquid thermal management system had best improvement in maximum temperature, an air-cooling required 2–3 times more power compared with other systems, and fin system bulked system to 40% more weight to the cell, which mean more weights. Despite possessing a slightly lower cooling performance, indirect liquid was more convenient approach than direct liquid cooling thermal management system.

Falcone et al. [29] (2021) investigated and compared air and liquid cooling methods using a cooling system for linearly arranged cylindrical lithium batteries surrounded by a solid structure and cooled by a forced convection cooling channel within the channel. CFD was used to evaluate thermal properties of lithium-ion batteries in order to determine temperature distribution; hence, temperature distribution lithium ion cells as consequence of the cooling system's geometrical structure was obtained. The cooling system can be considered a hybrid system consisting of thermal conduction between the batteries and the solid structure in the longitudinal direction and forced convection within the channels between the batteries. As a result, it was discovered that adding solid structure to lithium batteries improves system performance, hence battery temperature was minimized. It also shown that using a liquid cooling system was better to employing an air-cooling system in terms of low temperatures and battery pack density.

Park et al. [30] (2012) investigated numerically batteries configuration, coolant type (air and liquid) and system power consumption effect on system performance. Cylindrical battery temperature was predicted using one-dimensional heat conduction model using the finite difference approach, and the system power consumption was predicted using battery module based on the battery module configurations and operating conditions. Numerical study showed that large system with a small spacing was preferable for air cooling system, whereas a small system with a small spacing was preferable for liquid cooling system. The findings also showed that air cooling system consumed significantly high energy compared with liquid system, particularly under high heat load conditions. Although considering its benefits over the liquid cooling systems when heat load low, air-cooling system's power consumption was suitable.

3.3. Passive cooling system

Kizilel et al. [31] (2009) designed passive cooling system for high-energy lithium-ion cells subjected to stressful conditions, employing phase change material, and compared it to a cooling system that utilized air as the working fluid under normal and punitive conditions. A small and effectively configured passive cooling system dissipates heat faster than an active cooling system during high discharge rates while maintaining an appropriately uniform cell temperature to maintain the pack's optimum cycle life. This study showed how passive cooling using phase change material could help to prevent thermal runaway spreading in a single battery or nearby batteries because of a failure in a single one.

Rizk et al. [32] (2016) created a passive cooling system for a high-capacity battery pack (60 Ah capacity, 3.2 V voltage) for cooling functions by employing phase change and thermal conductivity principles. The design layout was combined water as coolant with copper heat pipes, combined with fins at the top to remove heat generated in the liquid due to the heat exchange operation and to increase the exchange area. The liquid that is contained in the heat pipe wall's porous structure in the evaporator portion transforms into vapor by absorbing heat from the battery surface. As it passed through the heat pipe to the condenser portion, the vapor transformed into liquid by releasing latent heat to surrounding.

Numerous researchers have compared the two systems (active and passive) to see which is more effective, to demonstrate this fact.

Karimi et al. [33] (2011) conducted a numerical study to demonstrate the relation of cell thermal behavior and the configuration characteristics. Using the fundamentals of heat transfer and the various properties of lithium batteries, the thermal and electrical performances of lithium batteries under the influence of different rates of discharge were determined. Several cooling methods, like force and natural convection cooling, have been tested for their effect on the lithium-ion cellist was noted that forced convection cooling is more effective than natural convection cooling since forced convection cooling provides more temperature uniformity and voltage distribution the model.

Sabbah et al. [34] (2008) numerically compared the effectiveness of a passive cooling system (PCM) versus an active cooling system for lithium-ion cells with characteristics suitable for utilization in hybrid vehicles at various discharge rates, working and ambient temperature. The findings were validated using experimental results as shown in Fig. 9. The phase change materials cooling mode surrounds the array of cells with a micro-composite graphite-phase change material matrix, meanwhile active cooling system employs air as coolant discharging in the spaces between the batteries that array in same part. The results showed that air-cooling is not an appropriate cooling system for controlling the battery's temperature high discharging levels and high working or ambient temperatures (40 to 45 ºC). In contrast, the passive cooling system may satisfy the operating range requirements under these same stressful conditions without the requirement for extra fan power.

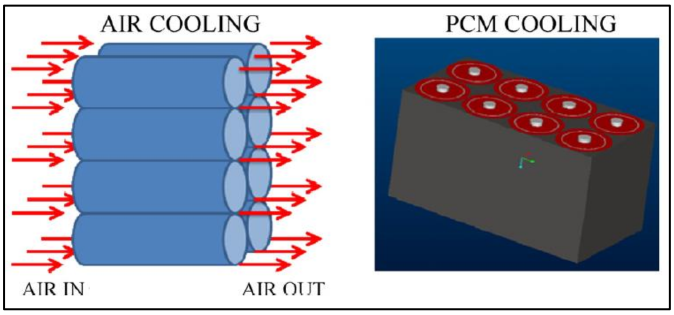

Fig. 9 Representation of active (air) cooling vs. passive (PCM) cooling**.**

3.4. Hybrid cooling system

Mousavi et al. [35] (2021) conducted a hybrid cooling system employing phase change materials with mini-channel cold plates to cool a prismatic-shaped lithium battery pack. Each model consists of five batteries, each of which has a cooling plate on both sides. It has been explored how battery model orientation affects cooling system performance. Hybrid mini-channel cold plates, another type of cold plate, have been studied by embedding phase-change materials (n-eicosane) into the cold plates. The effect of both types of cold plates was examined and compared using a constant rate of heat generation. The studies revealed that the orientation has an impact on cooling system work.

Behi et al. [36] (2021) designed experimentally thermal management system for cooling prismatic cells and managing temperature produced during operating under extremely high current and discharge rates as shown in Fig. 10. To control the accumulation of temperatures in the battery pack, use a cooling system comprised of heat pipes extended between the batteries and through which air flows. Batteries temperature was measured experimentally in absence of cooling conditions like natural convection, forced convection, and evaporate cooling and numerically validated using CFD software, specifically COMSOL. The experimental results showed that effect of natural convection and forced convection on battery temperature was 6.2% and 33.4%, respectively. Evaporative cooling method was effective in improve the current cooling system depend on the obtained results that showed that maximum temperature of the cell and module reduces by 35.8% and 23.8%, respectively.

Zhao et al. [37] (2014) designed hybrid thermal management system included water as coolant and heat pipe to deal with the heat rise of lithium-ion batteries during high discharge rate operations. The suggested system uses incredibly thin heat pipes to carry heat from the cell surfaces to the cooling sides. In this study, the cooling effects of the combined cooling system are investigated, and its performance is compared with that of other four types of cooling systems involving heat pipes as well as the natural convection cooling method. Two battery sizes, 3 Ah and 8 Ah, with various lengths of cooling ends, are used. Heat pipe system was developed to use combination of natural convection, fan cooling, and water-cooling strategies, allowing it to prevent battery pack's temperature to raise while using the least amount of energy and water spray.

Ling et al. [38] (2015) investigated experimentally a hybrid system that combines a passive cooling system represented by phase change material with an active cooling system such as forced air convection. In all cycles, this combination system reliably limited heat generation inside batteries and maintained maximum temperature below 50 ºC. According to research on airflow effects, the thermo-physical parameters of phase change material control the maximum temperature rise and temperature uniformity in the battery pack, while forced air convection plays a vital role in recovering the thermal energy storage capacity of phase change material. In addition, a numerical study is carried out and validated using experiment data to provide a theoretical understanding of thermo-physical changes in this hybrid system.

Amalesh et al. [39] (2019) provided a three-dimensional numerical study for modelling a hybrid cooling system combining Phase Change Martial (RT35) using different coolant (air, dielectric fluid (STO-50)) to control heat generated by a 38120P Li-ion battery pack. CFD used to analyze cooling system performance under different discharging rates (1, 2, and 3 ºC). The advantages of combination phase change material with different coolants (air, dielectric fluid (STO-50)) have been studied in five different cases. The simulation model was validated by comparing the results to previously collected data. when comparing coolants, results showed that combination Phase Change Martial and air or Phase Change Martial and liquid might further lower the cell temperature by 6 °C.

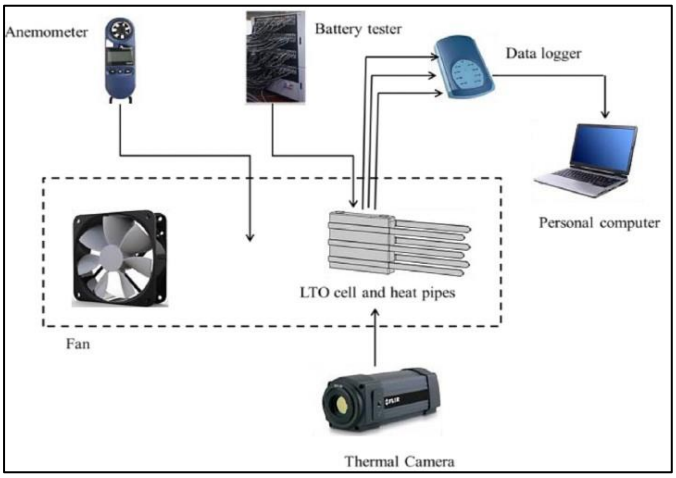

Fig. 10 the schematic of the test setup.

4. Conclusions

Lithium-Ion batteries are a promising strategy that the clean power rely on. The overheating is one of the problems that need to be overcome in this strategy. The survey of cooling systems followed in this field have led to the following conclusions.

1. There are several methods used to cool the lithium-ion batteries; passive, active and hybrid.
2. Cooling using air and liquids are classified as an active cooling system.
3. Air cooling systems better than liquid one.
4. Fig. 11 depicts weights of each cooling system. Most of the research are active cooling systems.
5. The acceptable working range of temperature is -20 to 60 °C under normal conditions, meanwhile the optimum working temperature range is 15 to 35 °C.
6. The preferable temperature difference between batteries is 5 °C or less.
7. Increasing temperature by 1 °C in the operational range of 30 to 40 ° C reduces battery life by 2 months.

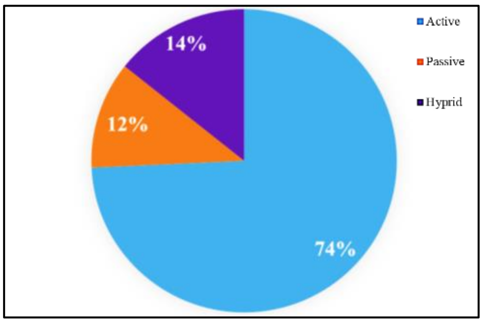

Fig. 11 Weight of researches regarding to cooling systems.

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