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A review on the applications of micro-/mini-channels for battery thermal management

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Abstract
This review of the literature explores the potentials of liquid micro-/mini-channels to reduce operating temperatures and make temperature distributions more uniform in batteries. First, a classification and an overview of the various methods of battery thermal management are presented. Then, different types of lithium-ion batteries and their advantages and disadvantages are introduced, and the components of batteries are described in detail. The studies conducted on the performance of micro-/mini-channels for cooling all types of rectangular and cylindrical batteries are reviewed, and the key finding of these studies is presented. It is shown that, in general, using counterflow configuration creates a rather uniform temperature distribution in the battery cell and keeps the maximum temperature difference below 5°C. The lowest battery maximum temperature is obtained for parallel and counterflow configurations in the straight and U-turn channels, respectively. In a parallel configuration, the peak point of the battery temperature is in the outlet area. However, in the counter-flow configuration, it occurs in the central region of the battery module. The survey of the literature further reveals that proper channel paths and flow configurations keep the battery maximum temperature within the safe range of $25\,°C < T_{max} < 40\,°C$. For such flow configurations, the pressure drop remains minimally affected.

Keywords Lithium-ion batteries · Thermal management · Micro · Mini-channels · Parallel configuration · Counter-flow configuration

List of symbols

A	Surface area (m^2)
D_h	Hydraulic diameter of the channel (μm)
j/f	Ratio of surface heat transfer to surface friction coefficient
L	Length of channel (mm)
MTD	Maximum temperature difference (K)
n	Number of channels
PCM	Phase-change material
NSGA-II	Non-dominant genetic algorithm
PEC	Overall thermal performance evaluation criterion
Re	Reynolds number
RSM	Response surface methodology
STD	Standard temperature deviation
T_{in}	Inlet temperature of fluid (K)
T_{max}	Maximum temperature of fluid (K)
V_{in}	Inlet flow velocity (ms^{-1})
Δp	Pressure drop (Pa)
ΔT	Temperature difference (K)

Greek symbols

α	The ratio of the inner surface to the total lateral surface of the channels
Δ	Absolute deviation
φ	Volume fraction

Subscripts

h	Hydraulic
in	Inlet
max	Maximum

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Introduction

For several years, the successful use of lithium-ion batteries as a source of energy in portable electronics such as mobile phones and laptops has made them essential for energy storage. Combining lithium-ion batteries with power grids, photovoltaic systems, and wind power to increase energy storage capacity has yielded acceptable results. Therefore, to reduce the carbon footprint produced by vehicles that use fossil fuels, the use of lithium-ion battery technology which has a long-life cycle is a favorable choice. One of the most feasible applications of lithium-ion batteries is the power supply in electric and hybrid vehicles [1]. Some of the factors that cause the heat generation in the batteries are electrical resistance during charge and discharge processes, high charge and discharge rate, reactions inside the battery and overheating of the electrode [2], electrolyte decomposition, pressure increase, cathode failure, and separator melting [3]. Battery temperature has a significant impact on both performance and battery lifetime [4]. Therefore, thermal management of lithium-ion batteries is crucial to minimization of financial losses, enhancing the battery lifespan, and ensuring their smooth and safe functioning. In general, both high operating temperature and low operating temperature reduce battery performance. The application of battery pack, the cell structure, and the conditions in which the battery is used, are the main factors that influence a battery thermal management system [5]. This review article provides an overview of micro-/mini-channel battery thermal management applications for various cell types. Because of the large surface-to-volume ratio of micro-/mini-channels and the superior cooling capability of liquids compared to that of gases, liquid-containing micro-/mini-channels have become suitable for intensive heat dissipation. Also, the use of different flow configurations, and increasing the number and layers of channels can reduce the excessive temperature increase of the cooling fluid at the outlet and create a more uniform temperature distribution over the base surface [6].

An overview of the use of micro-/mini-channels in cooling systems

The usage of small-scale heat exchangers can be taken into consideration in cases where there are material savings, space limitations, low mass, and large heat dissipation in small dimensions [7]. Previous studies demonstrated that micro- and mini-channels might provide effective cooling in a variety of devices. Numerous experimental and numerical investigations show that micro- and mini-channel heat sinks can effectively remove the heat from electronic components, for example, CPU chips [8], transistor modules [9], and diode lasers [10]. These heat exchangers, as compared to cooling fans, produce a more uniform temperature distribution in addition to lowering the temperature of microprocessors [11]. Given that the power consumption of liquid-based cooling systems is higher than that of air-based cooling systems, it is very important to employ methods such as using hydrophobic surfaces to reduce power consumption without reducing the cooling performance of the system [12]. Another application of micro-channel and mini-channel heat exchangers is in cooling and thermal energy collection in photovoltaic systems. At lower heat fluxes, the use of single-phase cooling is a practical solution for cooling these systems. However, for high heat fluxes, the use of boiling flows acts better [13]. The use of tapered microchannels with super-hydrophobic surfaces can reduce the temperature of small devices and significantly decreases the pressure drop of the system [14]. The use of nanofluids with magnetic properties in microchannels can enhance heat transfer in the system [15]. In many recent studies, micro-channels and mini-channels are used in refrigeration systems and heat pumps to improve system performance [16]. Other studies on the applications of microchannels include thermal management and separation processes in chemical reactors [17] and building heating with heat received from solar energy [18].

Among the novel applications of microchannels, one can point out their use in medical research such as transporting oxygen to organs [19], simulation of cervical fluid movement [20], inhibition of bacterial and viral growth [21], polishing of artificial heart valves [22], and drug delivery to blood hemodynamics [23].

The temperature of the battery cell should be maintained within a suitable temperature range to achieve the maximum potential of lithium-ion batteries. During operation, heat is generated by physicochemical processes that take place in the battery cell. Therefore, for the safe and optimal operation of batteries, proper thermal management systems should be used to reduce battery temperature in less time. As mentioned in the previous section, micro-channels and mini-channels have shown good cooling performance in different systems. On the other hand, many studies have been performed on the use of micro-/mini-channels for the thermal management of batteries.

The channels are classified according to their hydraulic diameter. Kandlikar and Grande [24] present a general classification for channel types in terms of the hydraulic diameter (D_h) of channels in Table 1. Channels with a hydraulic diameter of $200\mu m \geq D_h > 10\mu m$ are classified as micro-channels, and channels with a hydraulic diameter of

Table 1 Channel classification [24]

Channel type	Hydraulic diameter of channel
Conventional channels	$D_h > 3$ mm
Mini-channels	3 mm $\geq D_h > 200$ µm
Micro-channels	200 µm $\geq D_h > 10$ µm
Transitional micro-channels	10 µm $> D_h > 1$ µm
Transitional nanochannels	1 µm $> D_h > 0.1$ µm
Molecular nanochannels	0.1 µm $> D_h$

$3mm \geq D_h > 200\mu m$ are classified as mini-channels. More details on this classification can be found in Table 1.

A summary of the contents and a general classification of battery thermal management systems are provided in Fig. 1. In this figure, thermal management systems are classified based on parameters such as the arrangement of the battery cells, the type of coolant, the use or non-use of energy sources, and the combination of systems. The aim of this study is to investigate the potential of micro-/mini-channels in liquid-based cooling systems and their combination with other systems. In general, the use of micro-/mini-channels for the thermal management of batteries is divided into the following three schemes:

- Micro-/mini-channel cold plate
- Micro-/mini-channel duct
- Micro-/mini-channel heat sink

As displayed in the figure, liquid-based systems are one of the common techniques for the thermal management of batteries that have much higher heat dissipation than air. Liquids have higher thermal conductivity and heat capacity, and a thinner boundary layer than air. The use of an immersion cooling system has a higher and more uniform contact surface with the cells, so its thermal resistance is lower and it improves the cooling performance. Due to lower safety and chemical corrosion, the direct cooling system is not currently used in electric vehicles, but indirect cooling systems, such as liquid ducts, are widely used in battery cooling [25]. In liquid-based systems, a suitable sealing coating should be used to prevent liquid leakage. The use of small ducts and

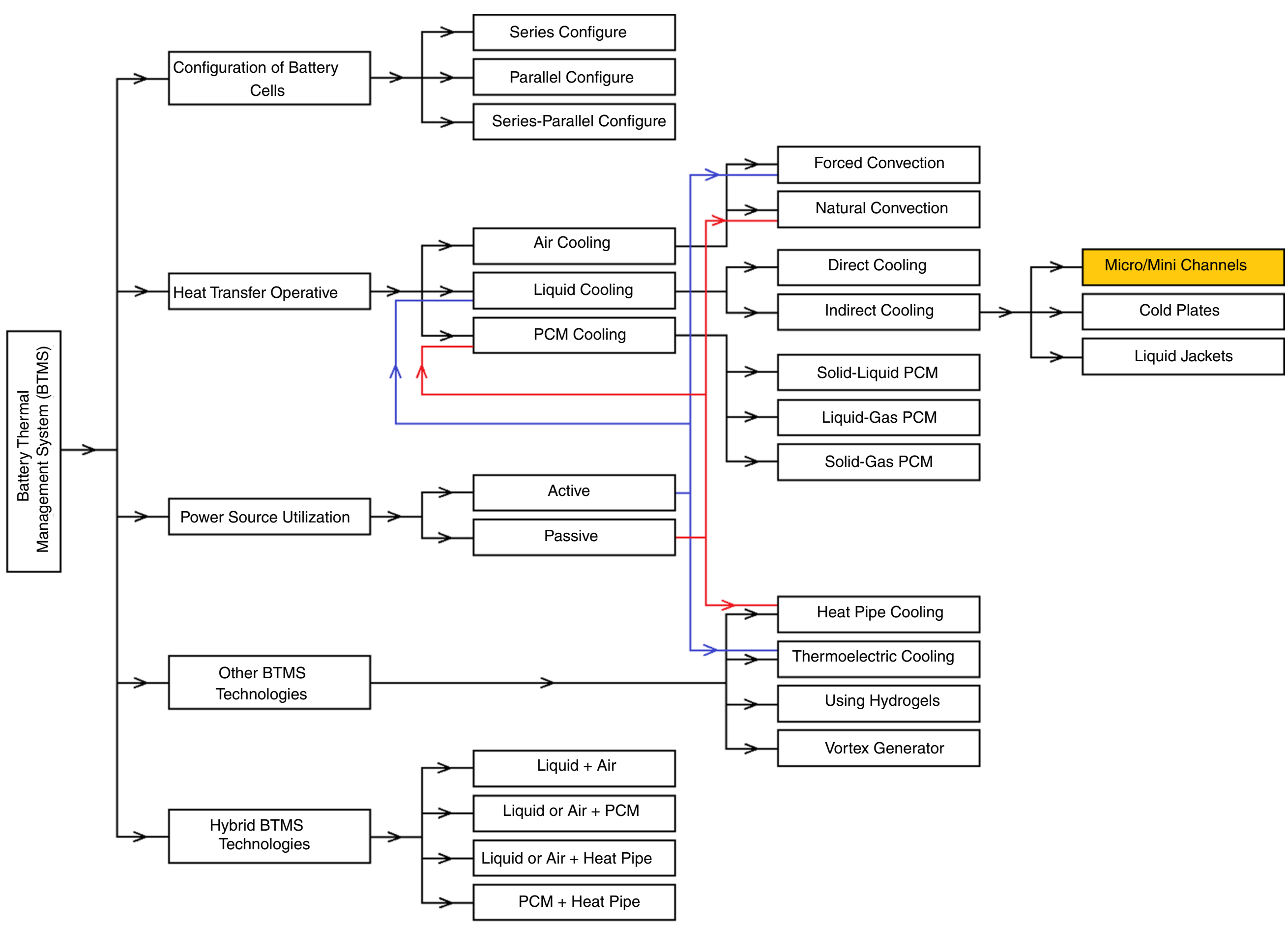

Fig. 1 General classification of battery thermal management systems

their integration with metal plates significantly increases the cooling performance of these systems, but the mass of the system increases. In these systems, channel geometry and heat transfer coefficient are two important factors in improving system performance. Also, in liquid-based systems, increasing the flow rate makes the battery temperature lower and more uniform [26]. However, it increases the pumping capacity and operating cost. Liquid cooling systems act better than cabin air-based cooling systems because the cooling capacity of liquid is greater than the air. However, liquid-based systems have disadvantages such as complexity, high mass, and high cost [27]. Large-scale liquid-based cooling systems are more suitable for battery packs and allow charging and discharging at high temperatures [28]. Deng et al. [29] reviewed the latest studies conducted on liquid-based thermal management systems. They analyzed the effects of factors, such as the type of coolant and the configuration of cells in the battery pack, on the system performance. Their results showed that the nanofluids with appropriate volume fraction increase the cooling performance. On the other hand, the combination of water with gallium alloy liquid metal, which has high thermal conductivity, improves the performance of the cooling system. The series/parallel configuration of cells in large battery packs also has better cooling performance. In cylindrical and rectangular batteries, the use of indirect contact mode can be applied with discrete tubes and cold plates, respectively [30]. The combination of liquid metals with low viscosity and high heat capacity with water creates a reasonably priced cooling fluid [31]. Forced cooling is another widely used cooling method used according to the required power, space, and number of cells. The efficiency of this method varies according to the flow velocity and the arrangement of the cells [32]. The air-cooling method has a wide commercial application compared to other cooling methods. In air-cooling systems, natural and forced convection is referred to as passive and active methods, respectively [33].

According to Fig. 1, one of the battery thermal management methods is the use of phase-change materials (PCM). The application of PCMs is a passive battery thermal management method with low operating costs. A PCM-based system has better cooling performance in rectangular batteries than cylindrical batteries. The use of PCMs extracts more heat and stores it in the form of sensible and latent heat. On the other hand, when PCM material is completely melted, it acts as a thermal insulator [34]. Heat pipes are another method of cooling that can be combined with cooling fans to decrease the operating temperature of the battery. Heat pipes have better thermal conductivity than PCMs, but their contact area with the battery is small and should be combined with cooling plates for better performance [35]. Thermoelectric cooling (TEC) is another method of thermal management of batteries. These systems can control the temperature of the battery well, but these elements are not applicable at all temperatures. Using TEC-based heat management systems instead of surface cooling triples the battery life and reduces the cost [36]. For a better understanding of the classification of battery thermal management systems, refer to Fig. 1. In general, those systems that work without an external source of power are classified as passive thermal management systems. This group is shown with red lines in Fig. 1 and includes PCM cooling, natural convection, and heat pipe cooling. Also, blue lines indicate active systems. These thermal management systems do require power sources and include liquid cooling, force convection (air and liquid flow), and thermoelectric cooling systems.

The purpose of the current review is to examine the potential of micro-/mini-channels containing liquid, as parts of active thermal management systems, to maintain the battery temperature within the safe range and reduce energy consumption. Therefore, parameters such as flow configuration, channel geometry, how to connect the channel to the battery cell, and the combination of micro-/mini-channels with other thermal management methods will be investigated. In addition, the power requirements of these cooling systems are further reviewed.

Introduction of lithium-ion batteries

One of the most important methods of power supply in portable electronics is the use of energy storage technology in lithium-ion batteries. The high energy density of these batteries has led to their widespread use in electric vehicles and grid energy storage in recent decades. Furthermore, lithium-ion batteries have a high potential for achieving energy stability and lower carbon emissions [37]. Lithium-ion batteries are composed of lithium metal oxides at the positive electrode (cathode) and carbon at the negative electrode (anode) [38]. As shown in Fig. 2, the cathode and anode make a two-electrical compound in an electrolyte solution separated by a membrane. Organic carbonate-soluble lithium salts form the electrolyte used in these batteries. The performance of lithium-ion batteries is due to the transfer of lithium ions in two phases. During charging, lithium ions are transferred from the positive electrode to the negative electrode, while an inverse trend can be observed when battery power is consumed [39].

Cost, cycle life, energy, power, safety, charge and discharge rates, and environmental impact are among the parameters that should be considered in the use of lithium-ion batteries in applications of portable electronics, electric vehicles, and energy storage [40]. The charge/discharge rate (C-rate) is defined as the steady current in amperes (A) that can be taken from or given in a battery of defined capacity (Ah) per unit time (h) [41]. Geometrically, the most widely

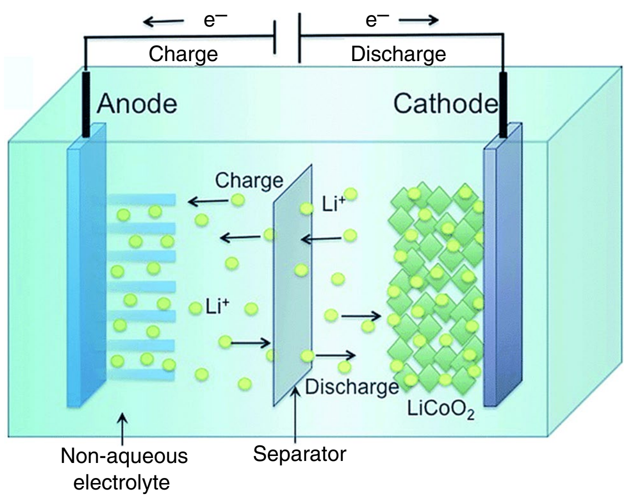

Fig. 2 Schematic diagram of a lithium-ion battery operation [39]

used lithium-ion batteries in the industry include cylindrical and rectangular batteries. Rectangular batteries are also divided into two types: prismatic and pouch. Fires and occasional explosions have been reported due to excessive temperature increases inside the batteries. There are also a few mechanisms of heat generation in batteries. Figure 3 shows an illustration of battery degradation brought on by an excessive temperature rise in the testing environment [42].

Failure to control this temperature will result in irreversible damage. Therefore, safety issues in lithium-ion batteries are one of the necessities of this technology. The salient advantages and disadvantages of lithium-ion batteries are described in Table 2. This table explains the high potential of lithium-ion batteries for use in energy storage systems.

As mentioned, the sensitivity of batteries to high temperatures is one of the disadvantages of lithium-ion batteries. At high operating temperatures (above 60 °C), the capacity of lithium-ion cells is severely reduced and thermal escape occurs if proper heat dissipation is not achieved. At temperatures of 130 °C and above, the separator melts inside the battery and the connection between the two electrodes causes a short circuit. In addition, at this temperature, many chemical reactions take place inside the battery, which leads to the production of large amounts of heat and hazardous gases [43]. Continued heat escape inside a battery cell causes heat to be dissipated to other closed battery cells, and leaked gases cause them to ignite and break down. On the other

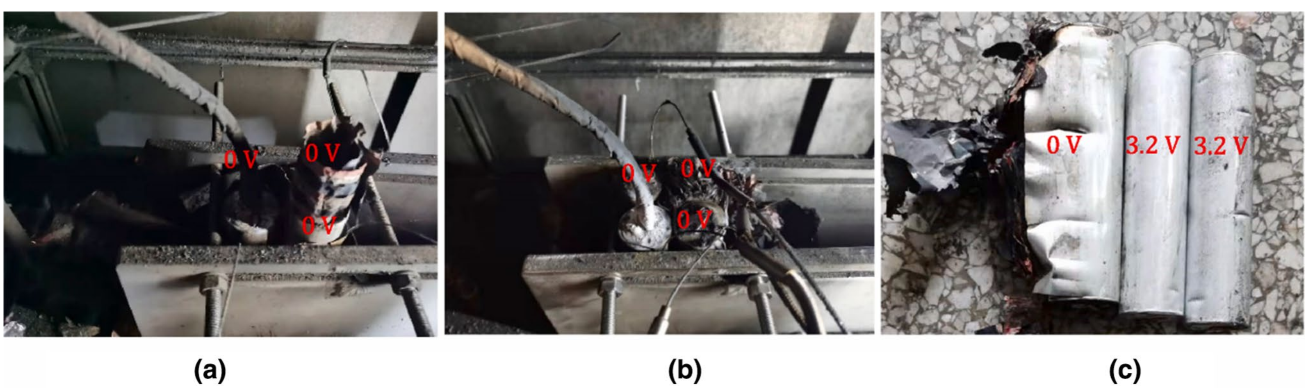

Fig. 3 Destruction of battery cells due to high temperature [42]

Table 2 Advantages and disadvantages of lithium-ion batteries

Advantages	Disadvantages
High energy density	High initial cost
High open-circuit voltage	Thermal runaway
Low self-discharge rate	Poor recycling
Eco-friendly	Need to advanced battery management system
Compact physical dimensions and low mass	Decreased performance over time
Long-life cycle	Sensitivity to high temperatures and the possibility of fire
Suitable operating temperature range	Probability of explosion at high pressure
Variety of technology in chemical structure	Improper performance at very low temperatures
High reliability	
Accessibility	
Ability to store renewable energy	

hand, heat transfer causes the continuation of internal chemical reactions and failure propagation. Therefore, in addition to preventing fires and extinguishing fires in the event of an accident, control and reduction of chemical reactions are also required to maintain safety [44].

Lindgren and Lund [45] studied the effects of temperature on battery charge and the performance of electric vehicles. They concluded that at very low temperatures, battery charging operation slows down. For example, at − 10 °C, the battery charge capacity is reduced by 15% compared to 20 °C. The efficiency ratio of the distance traveled to the power consumed is maximized when the ambient temperature is around 20 °C. The results of experimental studies by Lou et al. [46] also show that at temperatures below 20 °C, battery charging and discharging performance is significantly reduced, and in the temperature range of 20–40 °C, the effect of temperature on battery charging characteristics is almost insignificant. On the other hand, Bandhauer et al. [47] also concluded that the operating temperature range suitable for lithium-ion battery packs is 25 to 40 °C and the maximum temperature difference between the batteries should not exceed 5 °C.

Heat management methods using micro-channel and mini-channel

The construction and application of micro-/mini-channels are very expensive, time-consuming, and need precision devices. However, due to their high potential for cooling small areas, these systems are replacing conventional air-cooling systems in many industries. This section surveys the studies that used micro-/mini-channels for the thermal management of lithium-ion batteries.

Applications of microchannels in cooling and thermal management of batteries

Owing to the small size of these batteries and the large capacity of micro-channels for cooling small surfaces, the use of these channels in battery thermal management systems has resulted in good performance. In this section, the studies performed on the application of micro-channels in thermal management of lithium-ion batteries are reviewed.

In a numerical study, Mohammadian et al. [48] showed that the internal cooling of batteries using microchannels containing electrolyte features a better performance compared to external cooling using microchannels containing water. The possibility of thermal runaway in internal cooling is much less than that in external cooling [49]. Despite the superiority of the internal cooling system, the complexity of the system, lower level of safety, and technical limitations impede commercialization of these systems. For commercialization of external thermal management, researchers devoted their studies to optimizing and improving the performance of such systems. The main influencing parameter on the performance of these systems is the geometrical parameters. Experimental investigations by Pan et al. [50] show that manifold microchannels feature lower pressure drop and more uniform temperature distribution than traditional microchannels. Also, using the higher height-to-width ratio of the channels strengthens uneven temperature distributions [51]. On the other hand, increasing the channel depth improves the thermohydraulic performance, while it increases system mass and cost. As a result, Xu et al. [52] proposed a new micro-channel-based battery thermal management system where both sides of the battery are in direct contact with the fluid inside the channels. The experimental data and their numerical simulations showed that this plan gives a more uniform temperature and higher cooling capacity. Since in this design the fluid is in direct contact with the surface of the battery, it has better cooling performance and occupies a smaller volume compared to other designs. Direct contact with the cells requires corrosion-resistant material in the battery cell body. Rao and Zhang [53] proposed convergent wedge-shaped channels, which in addition to improving thermal performance of the system, increases the pumping power. Their design solves the problems of mass increase caused by the depth of the channel. Therefore, it can be concluded that in order to improve the performance of microchannel thermal management systems, the mass, cost, and complexity of the system are among its main challenges. Another type of microchannel-based thermal management system is the U-turn arrangement of channels in the cold plate, as shown in Fig. 4. The most important feature of these types of channels is to achieve a more uniform temperature distribution and a lower temperature coefficient by using a counter-flow configuration [54]. This type of flow configuration in serpentine microchannels also creates a more uniform temperature distribution [55]. In general, in these designs, the length of the microchannel has increased, which enlarges the pressure drop. Therefore, in the use of U-turn and serpentine microchannels, the use of optimization algorithms helps to achieve the best thermal performance for the battery cell with the lowest pressure drop. Jahanbakhshi et al. [56] used the counter-flow configuration in the microchannel heat sink consisting of wavy microtubes in the side walls. These authors achieved an acceptable performance in maintaining the battery temperature within the safe range.

Therefore, it can be concluded that, in the use of micro-channels in rectangular cells, increasing the contact area of the fluid with the solid wall and the counter-flow configuration has a significant effect on improving the system performance. Nevertheless, challenges such as mass, system complexity, and fluid pressure drop should be considered.

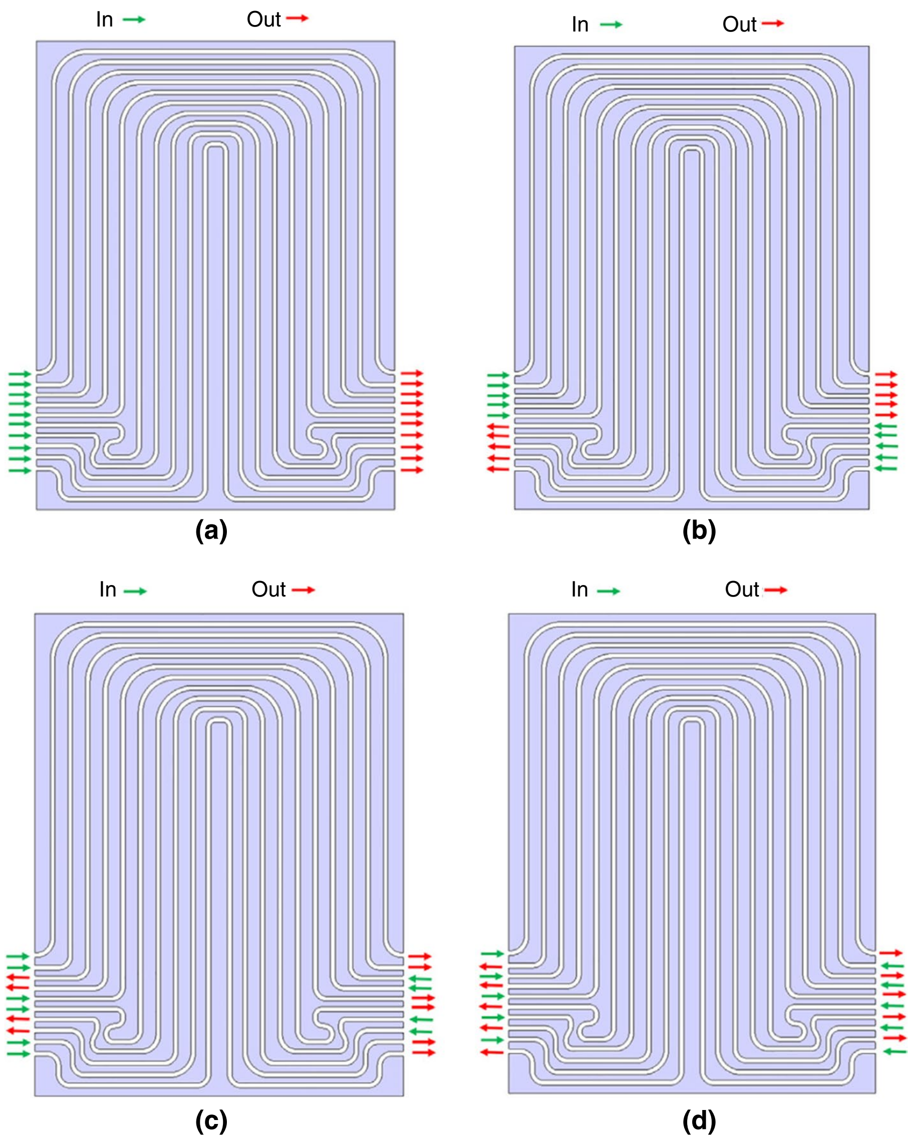

Fig. 4 Channel flow pattern layout **a** flow pattern I; **b** flow pattern II; **c** flow pattern III; **d** flow pattern IV [54]

The use of microchannels in rectangular BTMS is more common than in cylindrical BTMS. Azizi et al. [57] proposed cylindrical microchannel heatsinks for thermal management of each cylindrical battery cell. This design does not seem desirable in terms of commercialization due to the large mass and volume it occupies around each battery cell. Therefore, Wei et al. [58] suggested the use of flexible plate microchannels containing R141b refrigerant. Their design solves physical problems such as mass and volume, and in the case of refrigerant phase change, the heat transfer rate of the system increases. Generally, compared to water, liquids like ethylene, glycol, nanofluids, and refrigerants are more effective options. In summary, the advantages and disadvantages of microchannel-based battery thermal management systems can be expressed as follows.

Advantages of microchannels in BTMS:

- Using different coolants with higher cooling capacity.
- More heat dissipation and more uniform temperature distribution than air-cooling system.
- Increasing system performance using simple geometric changes in the channel.
- Improving system performance by modifying flow configuration.

Disadvantages of microchannels in BTMS:

- Increasing the system mass.
- The complexity of the system due to the use of pumps, energy sources, etc.
- Low performance of microchannel for larger cells.
- Higher production costs.
- High power consumption for coolant pumping.

Applications of mini-channels in cooling and thermal management of rectangular batteries

Mini-channels are widely considered for the thermal management of small systems. As shown in Table 1, micro-channels and mini-channels are separated according to the hydraulic diameter of the channel. Mini-channels application in battery thermal management systems is wider than micro-channels. Here, applications of mini-channels in cooling rectangular (prismatic and bag model) and cylindrical batteries are discussed.

Velocity, temperature, and direction of fluid flow at the inlet of mini-channels are the most important factors affecting the performance of thermal management systems. Huo et al. [59] investigated numerically the performance of a thermal management system based on mini-channel cold plates with different flow configurations. It was found that the effect of flow direction on the cooling performance is reduced at large flow rates. Increasing the mass flow rate first increases and then decreases the cooling efficiency of the cooling system. To reduce the temperature difference in large battery packs and reduce the required pumping power, Chen et al. [60] presented a cold plate design consisting of bidirectional symmetrical parallel mini-channels. Their design reduces the temperature difference of the battery pack by 77% and the pumping power by 82% compared to the conventional mini-channel cold plate. Xu et al. [61] concluded that the effect of fluid inlet temperature on cooling performance is much greater than inlet velocity. The uniform distribution of fluid from an input port to the mini-channels greatly reduces the maximum temperature and the temperature distribution difference of the battery cell. Therefore, uniform distribution of the inlet fluid is a prominent issue that should be considered [62].

By adjusting the flow configuration so that the inlet is on the tab side of the battery, the average temperature and the temperature difference were reduced to 27.1 °C and 0.65 °C, respectively, showing the best performance compared to other configurations [63]. Lan et al. [64] showed that with the use of aluminum strips comprising a mini-channel wrapped around a rectangular battery, the best performance was achieved when all the inputs are on one side of the channel and the outputs are on the other side. At flow rates above 0.8 l min^{-1}, the cooling performance increases slightly, and the required pumping power increases significantly. In another study, it was concluded that the mini-channel cooling system on the outer surface of the cell cannot stop the thermal runaway caused by damage to the battery cell, but it can prevent the thermal runaway from spreading to other cells and causing their failure [65]. The use of mini-channels on the lower and side surfaces of the rectangular battery module increases its cooling performance compared to the case where mini-channels containing coolant are used only on the side walls. Decreasing the inlet temperature of the coolant also reduces the maximum battery temperature and increases the temperature difference [66]. To maintain the average battery temperature in the range of 25–40 °C, the inlet temperature of 25 °C was found to be suitable for the coolant [67].

By simultaneously checking the heat transfer rate and pressure drop to achieve a uniform temperature distribution throughout the battery module, the number and width of the channels have an optimal value. Therefore, geometrical parameters such as length, width, height, and number of channels are examined.

Qian et al. [68] numerically investigated the effect of geometrical parameters on the thermal performance of a mini-channel cold plate shown in Fig. 5 for the thermal management of a Li-ion battery pack. Increasing the number of channels increases the cooling efficiency, but for more than 5 channels there is little improvement in system performance. Therefore, by using a cold plate consisting of 5 mini-channels, the temperature is reduced to a safe range. Increasing the width of the channel does not have much effect on reducing the maximum temperature, and in the best case, it reduces the temperature by 0.6 °C.

An et al. [69] found that increasing the width of the channels reduces the temperature difference of the battery surface in the low number of channels. Increasing the number and width of tubes reduces the pressure drop. Increasing width of the channel along the flow also has a positive effect on the system performance. Further, increasing the number of channels has an insignificant effect on the maximum temperature of the cell, but increases the temperature deviation [70]. Kong et al. [71] compared the performance of a cold plate containing divergent channels with conventional straight channels. Their results show that divergent channels have better thermohydraulic performance than conventional channels. Also, the use of two inputs and one output in divergent channels reduces the local resistance of the flow.

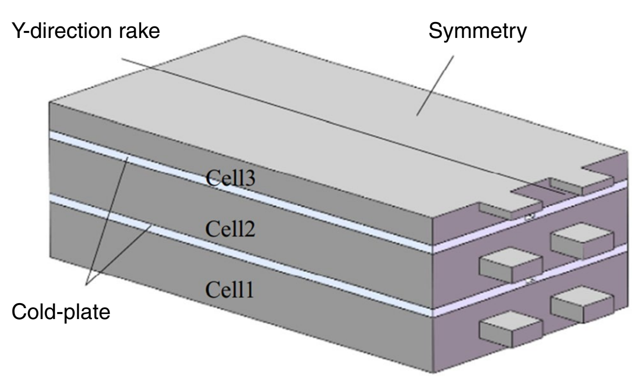

Fig. 5 Schematic of mini-channel cold plate system for prismatic battery considered by Qian et al. [68]

The new design decreases the maximum temperature difference by about 0.8 K, compared to conventional designs. Li et al. [72] showed that increasing the depth of channels also causes a gradual decrease in temperature deviation. Among the parameters, such as distance between the battery module and the cooling plate, depth of the channel, and horizontal and vertical widths of the channel, which are used to evaluate the performance of mini-channels, mini-channel depth has the greatest impact on cooling, temperature uniformity, and energy cost. Increasing the channel depth also reduces the standard deviation of temperature [73]. Vajravel et al. [74] concluded from experimental and numerical studies that the use of short channels in which the flow is always developing caused a significant decrease in overall thermal resistance compared to the conventional straight mini-channel. Chen et al. [75] investigated the effects of flow entering and exiting parallel channels from common inlets and outlets in a thermal management system based on a cold plate mini-channel. The results show that the use of parallel and Z-type input and output structures has a better cooling performance than the U-type structure. Symmetrical structures reduce the pumping power.

Spiral or serpentine channels are another type of mini-channels for battery thermal management by increasing the length of the channel. Using experimental and numerical techniques, Panchal et al. [76] found that in this model of channels, the temperature of the battery near the electrodes is higher than the temperature of the center of the battery surface. Also, increasing the discharge rate and cooling temperature increases the surface temperature distribution and the maximum battery temperature [77]. Jarrett and Kim [78] introduced a cooling plate including a serpentine channel for the cooling of rectangular batteries. Their results show that the channel with the largest possible width reduces the average temperature and pressure drop of the system to a great extent compared to other designs. Also, to achieve a uniform temperature distribution, it works best to use a channel that gets wider along the channel path. Uniformity of the temperature distribution is due to the equilibration of the cooling fluid velocity and the fluid–solid temperature gradient when the channel path is more open. Deng et al. [79] concluded that increasing the number of serpentine channels reduces the maximum temperature of the battery and makes its temperature distribution more uniform. Further, the design of the channels along the length of the battery acts better than the design along the width of the battery. Sheng et al. [80] investigated the performance of a cold plate consisting of two-layer serpentine channels. Their results show that the direction of flow and the location of fluid entry and exit have significant effects on the temperature distribution of the batteries and the power consumption of the system. Increasing the channel width reduces the pumping power significantly but does not have much effect on the temperature of the cells. Therefore, design of channels with suitable widths is particularly important. Also, using a channel with a double inlet and outlet results in a better cooling performance compared to a channel with a single inlet and outlet. Dong et al. [81] concluded from the numerical analysis of spiral channels that increasing the length and width of the channel first decreases and then increases the maximum temperature and temperature difference of the battery. In addition, increasing the height of the channel decays the thermal performance of the system. Among the parameters of height, length, and width of the channel, the greatest impact on the cooling performance is related to the length of the channel [82]. Li et al. [83] showed that the use of nanofluid in spiral mini-channels could maintain the maximum temperature and temperature difference within a safe range. Zuo et al. [84] numerically evaluated the performance of a single and double S-channel cold plate for cooling of a $LiFePO_4$ prismatic battery. They concluded that the use of a double S-channel has a more uniform temperature distribution than the single S-channel, but the maximum battery temperature is almost the same in both designs. The double S-channel also reduces the flow pressure drop by 73.88% compared to the single S-channel design.

Kalkan et al. [85] experimentally compared the thermal performance of a serpentine tube with a mini-channel cold plate that has branching structures along the channel. In terms of the uniformity of temperature distribution, the cold plate mini-channel has a better performance than the serpentine tube. Hence, mini-channels with branching structures along the channel will be examined in the following. Liu et al. [86] used a tree-type mini-channel heat sink to cool a prismatic lithium-ion cell at a discharge rate of 4 C. They observed that reducing the angle of the diagonal channels improves the heat transfer rate of the mini-channel heat sink and increases the pressure drop to a reasonable value. The use of tree-type mini-channels reduces the maximum temperature and the temperature difference of the battery cell compared to conventional straight channels. Deng et al. [87] introduced a cold plate with a network of leaf-like channels for the thermal management of rectangular batteries. Their results show that the use of leaf-like channels significantly reduces the maximum temperature and temperature deviation of the battery surface. Symmetric branching of the network has better thermal performance than offset branching of the network but slightly increases the pressure drop. Also, changing the number of channels and increasing the width of the main channel reduces the pressure drop based on heat transfer [88]. Wang et al. [89] proposed a spider-web design for the structure of mini-cooling channels for the thermal management of lithium-ion pouch-type batteries. They observed that the greatest impact on the cooling performance of the system belongs to the channel width. This follows by the number of channels and channel inlet angle. In general, under the same operating conditions, the spider-web design acts more efficiently than the conventional straight-channel design. Monika et al. [90] designed a cold plate mini-channel including Tesla valves to reduce battery temperature in forward and reverse flow cases. The results show that their design has a better cooling performance compared to conventional straight channels due to mechanisms such as mixing and flow branching. Although the reverse flow case has a higher pressure drop, it reduces the maximum temperature compared to forwarding flow designs and conventional channels. The most effective performance in this design is related to a cold plate with 4 channels and a distance between valves of 0.882 cm. Kalkan et al. [91] developed a cold plate design consisting of multi-branched mini-channels using the response surface method for the thermal management of lithium-ion batteries. Experimental results show that the new design improves the cooling performance of the system compared to conventional channels. Also, parameters of channel width and depth, the distance between branches, and the number of channel intersections are among the geometrical factors affecting the performance of the system.

Another design of mini-channels widely used in thermal management of batteries is U-turn mini-channels. Shen et al. [92] numerically studied the thermal performance of the U-turn cold plate mini-channel for the thermal management of prismatic lithium-ion batteries. They investigated the effect of different inlet configurations, inlet temperature, and the number of channels on cell temperature at different discharge rates. Increasing the number of channels reduces the pressure drop and the maximum cell temperature and increases the cell temperature difference. In this design of the channels, the lowest cell temperature and the lowest temperature difference are obtained when the flow inlet is placed on one side and the output is placed on the other. Lee et al. [93] used a three-dimensional model to study the performance of a U-turn mini-channel cold plate for the thermal management of a battery cell and a 14-prism lithium-ion battery pack. They concluded that the low coolant velocity causes the maximum temperature of the battery cell to raise, and the risk of fire and heat escape is the consequence of this temperature rise. Adequate coolant inlet velocity reduces the maximum temperature and temperature difference of the battery cell to less than 30 °C and less than 5 °C, respectively. Chen et al. [94] concluded from experimental and numerical studies that the use of multi-objective design optimization (MMDO) algorithm is a very efficient method to optimize the thermal performance of the U-turn mini-channel cooling plate in the thermal management of batteries. Karthik et al. [95] used a multi-objective optimization technique (MOO) to optimize the thermal management system based on U-turn mini-channels for a lithium-ion battery pack consisting of two prismatic cells. The genetic algorithm method has been used to obtain the set of optimization solutions. Finally, they concluded that the maximum mass flow rate, power consumption, and maximum flow pressure could be reduced by 66.33%, 43.56%, and 38.10%, respectively, while keeping the temperature increase and temperature distribution of the battery within the nominal range. Jin et al. [96] experimentally compared the performance of a conventional straight-plate mini-channel with a new design. They provided a U-turn plate mini-channel in which diagonal ribs were used. They observed that the mini-channel with the new design has a higher heat transfer coefficient than the conventional direct mini-channel. The use of ribs in the flow path, in addition to increasing the contact surface between the solid and the fluid, causes the flow to be always developing state, thus increasing the heat transfer rate of the system. Guo et al. [97] numerically investigated the performance of a thermal management system based on a mini-channel cold plate with pin fins. Their results show that copper pin fins can improve heat transfer and reduce pressure drop. Also, pin fins that are set vertically have a 4.54% more efficiency index than horizontal pin fins.

According to Fig. 6, Monica and Data [98] presented six different mini-channel designs for the cooling of pouch-type lithium-ion batteries based on liquid cooling. The results of their numerical simulations showed that the serpentine and hexagonal designs have more uniform temperature distributions and a lower average temperature than other designs. The Pumpkin channel design has the lowest pressure drop and pumping power and the highest ratio of surface heat transfer to surface friction coefficient (*j*/*f*) among other designs. Although the Pumpkin channel design has the highest cooling performance factor, the best thermal performance is attributed to the serpentine and hexagonal designs. These designs improve the uniformity factor by 3 to 16% at a mass flow rate of 5 kg s^{-1}. The Pumpkin channel design has good hydraulic performance because it prevents the vortex and impact flow that occurs in the conventional straight design and reduces the flow resistance. As a result, in the Pumpkin (or streamline) design, the pressure drop is reduced, and further optimization of this design can create more temperature uniformity at the surface of the battery module. If the curved channels are designed to cool the corners of the cold plate as well, in addition to maintaining the pressure drop reduction as compared to the straight design, the temperature distribution is uniform and the maximum temperature on the battery surface is lower than the straight design [99]. Fractal mini-channels with hexagonal structures have a very high cooling performance due to the frequent interruption of the boundary layer and high mixing of the flow. The results show that the fractal mini-channels with hexagonal structures have a more uniform temperature distribution and a lower maximum temperature at the base surface compared to the straight channels [100].

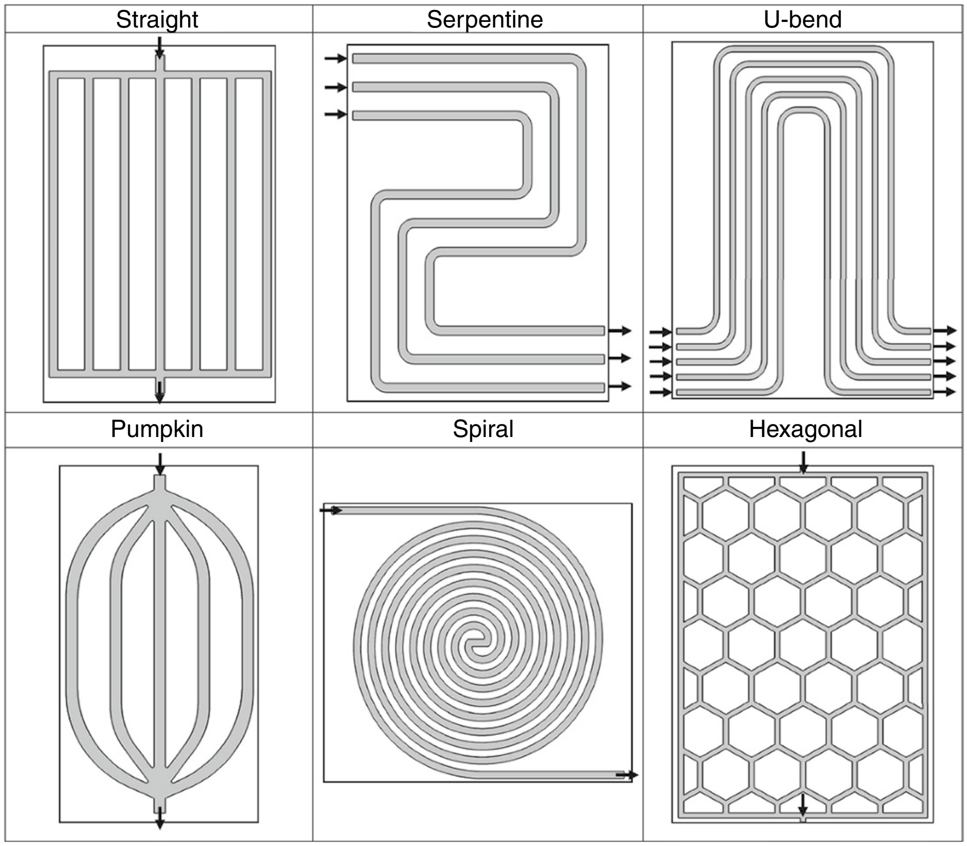

Fig. 6 Designs of six different cooling plate designs [98]

If the straight design uses the right branching angle for uniform distribution of the incoming fluid to the mini-channels, the ratio of surface heat transfer to the surface friction coefficient (*j*/*f* factor) increases. By increasing the slope angle of the inclined channels, the performance of the mini-channel cold plate increases. In practical applications, increasing the angle of inclination causes the corners of the cold plate not to be cooled well in contact with the battery, which leads to a reduction of the uniformity of temperature distribution [101].

Another way to improve the performance of mini-channels is to change the shape of the lateral walls. Amalesh and Narasimhan [102] investigated the performance of straight mini-channel cold plates with seven different designs in terms of flow path geometry. The channel design with a circular slot in the sidewall and the channel with a zigzag sidewall show the best cooling performance compared to other designs. The circular and zigzag slit designs create very good temperature uniformity, and at high discharge rates, the temperature distribution difference is between 1 and 2 °C. On the other hand, the zigzag wall design greatly increases the pressure drop, but the slit circle design has a much lower pressure drop than the zigzag design and is about 3 times less. Therefore, in terms of overall thermohydraulic performance, the mini-channel design with a circular gap in the sidewall was selected as the best design in their study. Salimi et al. [103] used a cold plate containing wavy mini-channels for the thermal management of pouch-type batteries. Their results show that changing the wave amplitude in wavy walls improves the uniformity of temperature distribution. Further, the use of counter flow in conventional wavy channels considerably affects temperature uniformity compared to new wavy channels. So that the use of counter flow in conventional wavy channels reduces the temperature difference by about 73.1% compared to co-flow. Finally, Zhou et al. [104] showed that in the study of battery cooling systems, the effect of various vehicle shocks and vibrations should be considered. Investigations show that heat transfer performance in the system under vibration increases and causes a decrease in the maximum temperature and the temperature difference of the cold plate.

A review of studies on thermal management systems for rectangular batteries (pouch type and prismatic type) shows that the cold plates consisting of mini-channels are mostly used in this type of system. The results show that geometric parameters, such as width and the number of channels, considerably affect cooling performance and uniformity of temperature distribution in this type of liquid cooling system. Increasing the mass flow rate and decreasing the coolant inlet temperature significantly decrease the maximum temperature of the batteries. The use of channels at which the distribution of fluid at the inlet is more uniform (as in the Pumpkin scheme) decreases the system pressure drop and thus the pumping power consumed for the fluid flow. If the design of the mini-channels is such that the distribution of the coolant can be the same throughout the battery surface, more uniform temperature distribution at the battery surface is obtained. The use of counterflow also reduces the difference between the minimum and maximum temperatures of the battery. The use of a forced coolant system by mini-channels has an acceptable performance in maintaining the safe temperature of rectangular batteries. Reducing power consumption and system mass can also increase the performance of this type of thermal management systems.

The advantages and disadvantages of the rectangular battery thermal management systems based on mini-channel can be summarized as follows.

Advantages of mini-channels in rectangular BTMS:

- Better performance than microchannel for larger cells in battery packs.
- Significant improvement of performance with minor geometry changes.
- Improving system performance by modifying flow configuration.
- Using different coolants with higher cooling capacity.
- Stronger heat dissipation and uniform temperature distribution than the air-cooling system.
- Enhancing system performance only by modifying the flow path.
- Suitable for high heat fluxes (or high charge/discharge rates).
- Prevention of thermal runaway in the battery pack.

Disadvantages of mini-channels in rectangular BTMS:

- Increasing the system mass.
- Complexity of the system due to the use of pumps, energy sources, etc.
- High power requirements for coolant pumping.
- Increased pressure drops in longer channels.
- Occupying more space in the battery pack.

Applications of mini-channels in cooling and thermal management of cylindrical batteries

As mentioned earlier, another common type of lithium-ion battery is a cylindrical battery. Therefore, using the mini-channels in thermal management systems of cylindrical batteries is geometrically different from rectangular batteries and the contact surface of cooling channels with cylindrical batteries is very important.

In 2014, Fan et al. [105] investigated the effect of oblique-finned walls compared to conventional solid walls in cylindrical mini-channel heat sinks. Because of the mixing of the flow inside them, the cylindrical oblique fins increase the thermal performance and thus reduce the surface temperature compared to conventional designs. However, conventional cylindrical fin heat sinks without edge effects can exhibit a more uniform and lower temperature distribution due to flow mixing. To cool cylindrical lithium-ion batteries, Zhao et al. [106] placed them in cylinders consisting of liquid mini-channels in the wall. Establishing a fluid flow within the mini-channels and examining the flow direction configurations show that this system is suitable for the thermal management of cylindrical batteries. For more than 8 channels, T_{max} does not decrease significantly, so it is not necessary to increase the number of channels to more than 8. At a constant input flow rate, increasing the size of the channel inlet reduces the heat dissipation of the system. Yet, this design adds a lot of mass to the system due to the large volume of solids. Therefore, to cool a battery module consisting of six cylindrical cells, Rao et al. [107] present a new design in Fig. 7. The aluminum blocks have been used to increase the contact surface and their interior mini-channels to augment the battery heat dissipation. System performance with a variable contact surface is also compared to the constant contact surface. Increasing the contact surface of the battery with its adjacent cell is designed with three slopes of 1 mm, 2 mm, and 3 mm. By comparing these three surfaces with the fixed contact surface (24 mm), it can be seen that the temperature difference of the system is reduced. The maximum decrease in battery temperature is less than 40 °C, which is similar to the case of the constant contact surface. In comparison with the constant contact surface, the cooling system mass was reduced by about 20, 29, and 47%, respectively. Therefore, these systems have good flexibility in reducing the mass of the system. In a similar design, Du et al. [108] used solid cooling blocks on the outer surface of

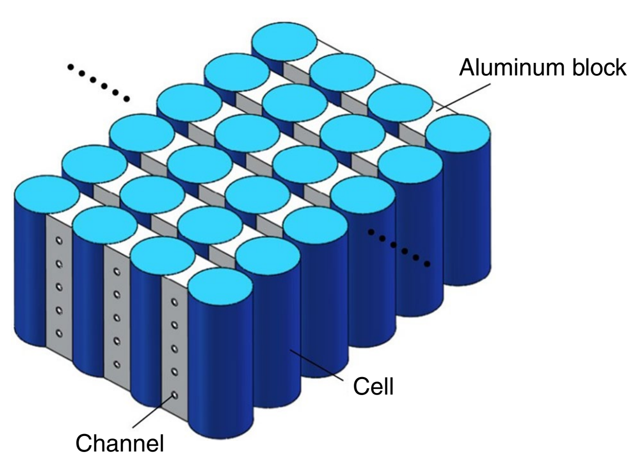

Fig. 7 Schematic of liquid cooling system for the cylindrical battery module [107]

the side row of batteries, which simultaneously increased the performance and mass of the system.

Therefore, it is important to increase the contact surface of the batteries with the channels or reduce the thermal resistance between the cooling system and the battery cell. Lv et al. [109] proposed the use of graphene oxide-modified silica gel to fill the space between cylindrical batteries and water-cooled pipes. Adding graphene oxide to silica gel increases the thermal conductivity, and as a result, the heat dissipation of the battery by the cooling pipe increases, and the temperature distribution of the battery module becomes more uniform. Lai et al. [110] used circular mini-channels with 3 curved contact surfaces and 18,650 cylindrical cells for the thermal management of batteries. Contact angle, contact height, and inner diameter of the channels were among the geometric parameters investigated in their study. Increasing the inner diameter of the channels reduces the pressure drop of the system while having little effect on the maximum temperature and temperature distribution. Decreasing the contact height at the current inlet reduces the temperature difference, but only partially increases the maximum temperature. Increasing the contact angle reduces both the maximum temperature and the temperature difference of the batteries. Finally, it was found that the system was able to reduce the maximum temperature to less than 313 K at the discharge rate of 5C and keep the battery temperature difference at 4.137 K. Zhou et al. [111] used a liquid-based system with half helical channels for the thermal management of cylindrical lithium-ion batteries. If the mass flow rate is optimal, parameters such as pitch and number of helical channels have little effect on cooling performance. In addition, by increasing the diameter of the channel, positive effects on the cooling performance of the system were observed.

Falahat et al. [112] used helical mini-channel heat sinks along cylindrical batteries to improve the thermohydraulic performance of mini-channel cooling systems. They used two types of helical channels with angles of 45 ° and 60 ° and compared the experimental results with straight channels. Their results showed that reducing the helix angle increases the heat transfer of the system, but it causes an increase in the pumping power and pressure drop of the system, so that at the highest Reynolds number, the total thermal resistance in 45 ° and 60 ° channels decreases by 50.9% and 32.2%, respectively, compared to straight channels. Finally, it was found that helical mini-channels are a very effective cooling design for lithium-ion batteries. Abdulhaleem et al. [113] used wavy heat well mini-channels along the length of cylindrical batteries to improve the thermohydraulic performance of liquid-based systems. Since the completely wavy mini-channels increase, the pressure drops significantly, so a straight-wavy combined channel is used in their new design. The results show that straight-wavy channels have lower pressure drop than completely wavy channels. Further, straight-wavy channels reduce the temperature well compared to conventional straight channels. Cao et al. [114] numerically investigated the performance of corrugated liquid cooling channels for the thermal management of battery packs consisting of 22 modules of 18,650 cylindrical batteries. Increasing the charge and discharge rates has a greater effect on reducing the uniformity of the closed battery temperature than increasing the operating temperature. They concluded that at a discharge rate of 2C, the use of a flow rate of 36 L min^{-1} reduces the maximum temperature and surface temperature difference to below 312 K and 11 K, respectively. Finally, to improve the uniformity of temperature distribution, they proposed geometric modification of these mini-channels.

In corrugated channels, increasing the contact angle of the channel with the surface of the cylindrical battery and increasing the mass flow rate increase the heat dissipation from the battery and the uniformity of its temperature distribution [115]. Increasing the contact area of channels and batteries too much can reduce the cooling performance of the system. Increasing the charge/discharge rate (C-rate) of the battery leads to an increase in the maximum temperature and a decrease in temperature uniformity in the battery module [116]. In general, in cooling systems of cylindrical batteries, the greatest impact on the cooling performance belongs to the contact angle. This follows by fluid inlet velocity and the number of channels. Among these factors, the contact angle has the most impact and the number of channels has the least impact on the cooling performance of the battery thermal management system [117]. Tang et al. [118] used heat-conducting blocks in contact with the battery and flat tubes containing the cooling fluid to cool the cylindrical lithium-ion battery modules. Their results showed that increasing the contact angle of the battery blocks and cells increases the heat transfer zone and thus reduces the maximum temperature. It also augments the temperature uniformity in the battery module. When the gradient angle increases by 15° and the fluid inlet velocity is 0.015 ms^{-1}, the temperature difference between the battery module at the end of the discharge process is 2.58 °C and the maximum temperature is 29.47 °C. In a numerical study, Wiriyasart et al. [119] studied the performance of nanofluid corrugated mini-channel for cooling cylindrical lithium-ion battery modules (18,650 type). According to Fig. 8, the surface of the corrugated mini-channel is in contact with the surface of the batteries. Due to the helical structure of this channel, there is a channel row between two rows of batteries. They found that the use of a two-layer corrugated mini-channel with an asymmetric flow structure has better performance than a single-layer micro-channel. In the two-layer design, the maximum battery surface temperature is 27.59% lower than in the single-layer design. Also, the two-layer design has the lowest average surface temperature compared

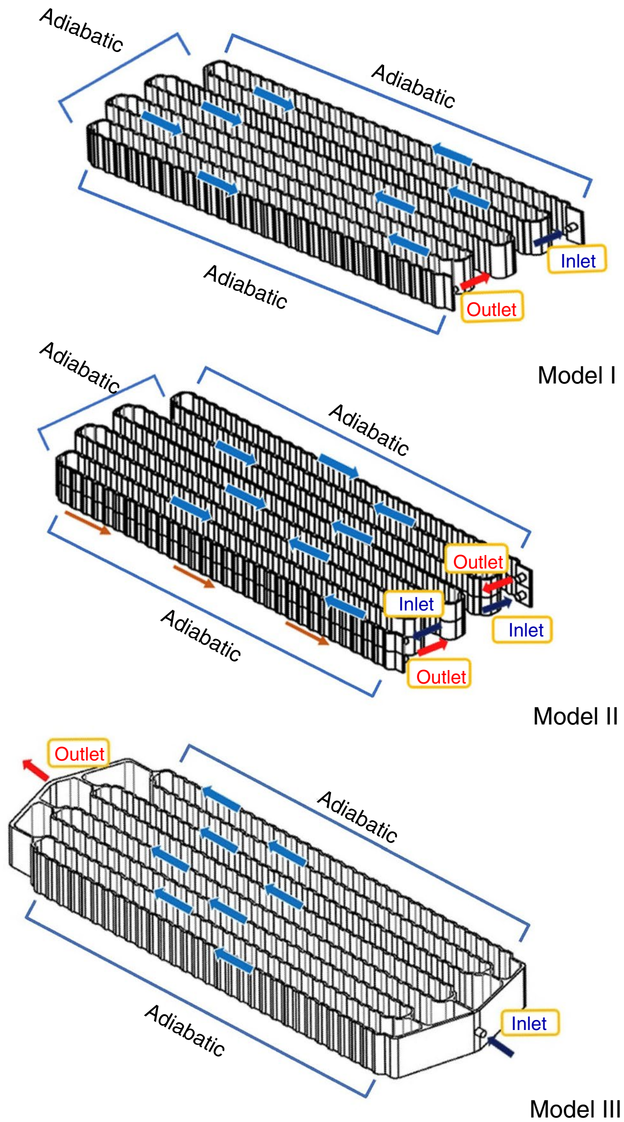

Fig. 8 Schematics of corrugated mini-channels: Model I (parallel mini-channels with a single-inlet and single-outlet manifold and parallel flow), Model II (two-layer serpentine mini-channel with two-inlet and outlet manifold and counter flow), Model III (serpentine mini-channel with a single-inlet and single-outlet manifold) [119]

to the helical single-layer design and the parallel single-layer design. The temperature distribution of the two-layer design is more uniform than other designs. This is because the use of counterflow in the two-layer design causes the heating effect in the lower layer to be repelled by the coolant in the upper layer, resulting in a more uniform distribution of the battery cell temperature and a lower average temperature. On the other hand, the two-layer design features the highest pressure drop compared to other designs.

Using a parallel cooling system provides a lower maximum temperature ($T_{\max}$) and temperature difference (ΔT) as compared with serial cooling in a cylindrical battery module. Moreover, the use of counterflow in a parallel structure shows the best thermal performance [120]. To use flat serpentine channels for the thermal management of cylindrical batteries, the appropriate contact angle between the cell surface and channels should be considered and the use of shorter flow path channels with counter flow improves the uniformity of temperature distribution [121]. Adding the baffles to the corrugated channels increases the coolant flow mixing. As a result, heat transfer is improved, and more uniform temperature distribution is observed in cylindrical battery cells. Increasing the number and height of the baffles rises the cooling performance in the battery pack, but causes a significant pressure drop in the coolant flow [122].

Yates et al. [123] investigated the performance of two designs, including mini-channel-cooled cylinders and channel-cooled heat sinks, in terms of cooling of cylindrical battery packs. At a mass flow rate of 5×10^{-5} kg s^{-1}, the use of both designs reduces the maximum temperature and temperature difference between battery packs to less than 313 K and 3.15 K, respectively. The mini-channel-cooled cylinder design has a lower maximum temperature than the other design, but its temperature difference is larger. In general, the mini-channel-cooled cylinder design has a higher cooling performance and much less mass than the other design, but the system is more complex. Li et al. [124] proposed two designs, including a serpentine channel and a U-shaped channel, for the cooling of cylindrical lithium-ion batteries. The serpentine channel design uses corrugated channels similar to the channels used by Wiriyasart et al. [119] in Fig. 8. In the U-shaped channel design, straight channels are used and on the outer surface of these channels, curved grooves are installed for better contact between the battery and the channel surface. The straight-channel structure in the U-shaped channel design gives a lower pressure drop compared to the serpentine channel design. However, their cooling effects are almost identical. Finally, using a multi-objective optimization model, it is determined that in the optimal design, the temperature difference increases from 3.82 K to 3.93 K, and the standard temperature deviation (STD) decreases. The optimization shows that the maximum temperature difference (MTD) and the maximum closed battery temperature of the cylindrical batteries are 3.46 K and 301.63 K, respectively, which are decreased by 7.49% and 0.04%, compared to the original design, respectively [125].

Dong et al. [126] investigated the cooling performance of a double-helix structure mini-channel for the thermal management of a cylindrical battery. In their design, the cylindrical battery cell is placed inside an aluminum cylindrical sleeve, and the liquid flow through the helix channel embedded in the sleeve dissipates the heat generated by the battery. They observed that the optimal values for the parameters of mass flow rate, helix pitch, and channel diameter are 1.94×10^{-3}kg s^{-1}, 100 mm, and 0.4 mm, in which the system can reduce the maximum temperature of the battery below 40 °C. Zhang et al. [127] investigated a thermal management system based on non-metallic materials such as silica gel in terms of cooling performance. Their study has been done to reduce damages caused by the deformation and tearing of metal systems after collisions and incidents. Experimental results show that the use of a thermal management system based on non-metallic tubes can reduce the temperature of cylindrical cells at low discharge rates. However, the use of these tubes is not suitable for high battery discharge rates, and their commercial use also needs more investigation in the future.

In 2022, Fan et al. [128] used different structures based on the triply periodic minimal surface to create flow mixing and improve cooling performance in tubes. The results showed that the maximum temperature and the temperature difference of the cylindrical battery module at the inlet flow rate of 0.003 kg s^{-1} are reduced by about 9% and 59.8%, respectively, compared to the conventional straight tubes. The improvement of cooling performance in sheet structures based on the triply periodic minimal surface is due to the large surface area and meandering geometry, but these factors increase the pressure drop. Yin et al. [129] investigated the effect of vehicle vibrations on the performance of liquid thermal management systems for cylindrical batteries. Classic serpentine channels have been used for better exploitation of vibration effects. The cooling performance of the new vibration system can reduce the average wall temperature by 1.8 K and increase the average Nusselt number by about two times. This is while the new design has a slight effect of increasing the pressure drop of the system. Sun et al. [130] used aluminum cooling jackets consisting of liquid circular mini-channels for the thermal management of cylindrical batteries. The results show that this system can reduce the temperature of the cell core and improve the uniformity of the battery temperature. Further, by optimizing this system, it is possible to reduce the risks of thermal runaway emissions.

Integrating a water-based thermal management system with a new cooling component such as water channels can improve the system's cooling performance. Even in unfavorable working conditions such as high ambient temperature and high discharge rate, the use of this system decreases the battery temperature and make the temperature distribution more uniform [131]. Li et al. [132] investigated the performance of cooling plates consisting of mini-channels and circular holes for placing cylindrical cells by numerical modeling. Their results show that the use of an aluminum enclosure can be highly effective in heat dissipation and uniformity of temperature distribution. The use of counterflow reduces the temperature difference by 16.5% compared to the parallel flow. Also, the use of channels with a square cross section has better heat dissipation and lower flow resistance compared to the oval and circular channels. Finally, it was found that using this system is efficient to reduce the maximum temperature and temperature difference of the battery pack to the safe range for the 4C discharge rate.

The results showed that in the use of mini-channels for cylindrical cell cooling, the contact angle of the channels with the batteries is very important. In many cases, solid blocks and spacers are used to make better contact between the cooling system and the battery cell. A proper contact angle improves the rate of temperature reduction and makes temperature distribution more uniform. It also reduces the mass of the system. Due to the curved surface of cylindrical batteries, corrugated channels are used in many cases. Although corrugated channels have a simpler structure, they increase the pressure drop of the coolant flow. Inlet rate of fluid flow and the number of channels are other important parameters that affect the system's performance. However, increasing the inlet flow rate raises the pumping capacity. An increase in the number of channels augments the mass of the system. Therefore, to achieve an optimal system, in addition to improving the uniformity of battery temperature, suitable pumping power and mass should be considered.

Advantages of mini-channels in cylindrical BTMS:

- Uniformity of temperature distribution in counter flow.
- Heat dissipation and proper contact surface in wavy channels.
- Better heat dissipation than air cooling in a greater number of battery cell.
- The ability to reduce the temperature of the battery cell core.
- Improving the performance of the system with geometrical changes in the cross section of the channel along with reducing the pressure drop.

Disadvantages of mini-channels in cylindrical BTMS:

- System mass increase.
- Not complete contact of the channel surface with the cell surface.
- Higher pressure drops in long wavy channels.
- Complexity of system.

Combining micro-/mini-channels with other battery thermal management systems

Here, some hybrid schemes that combine micro-/mini-channels with other battery thermal management systems are introduced.

Liquid cooling-based systems have particularly good cooling performance, and the use of PCM cooling increases the uniformity of temperature. Rao et al. [133] designed a high-performance heat management system. They combined the liquid-based mini-channels and PCM cooling blocks. They found that the PCM/mini-channel system can reduce the maximum battery temperature to 320.6 K, while under the same conditions, the PCM cooling system reduces the maximum temperature to 335.4 K. Moreover, to achieve a safe temperature range, there should not be less than 4 mini-channels, and a higher number of mini-channels lead to more temperature uniformity. Kshetrimayum et al. [134] developed an integrated PCM design and micro-channel cooling plate for cooling of 18,650 lithium-ion battery modules. In addition to the cooling performance of the system, the effects of mechanical damage caused by driving accidents, such as nail penetration on heat dissipation and heat escape, have also been investigated. They concluded that the use of counterflow in the channels prevents the propagation of heat to adjacent cells. On the other hand, the simultaneous use of PCM and the liquid-based system helps to maintain the temperature of the coolant below the boiling point and prevents the negative effects of coolant boiling. By adding metal foams to pure PCM, Bamdezh et al. [135] formed a phase-change composite material that surrounds a cylindrical cell. Inside this material, direct channels containing water are used in the axial direction of the battery. The results show that a part of the water-cooling capacity is spent on PCM freezing. Further, increasing the tangential conductivity and the thermal conductivity has positive effects on the reduction of the average temperature and the temperature difference of the battery cell. The raise in the axial and radial conductivity has insignificant effects on the time changes in the mean temperature of the battery cell.

The use of micro-/mini-channels around rectangular cells and in the presence of PCM has acceptable performance in the thermal management of lithium-ion batteries. Mustafa et al. [136] used a bionic geometry of channels containing nanofluids and PCM medium, and Rostami et al. [137] also used helical micro-channels in the presence of PCM for rectangular batteries. Their results showed that at low cooling fluid velocities, PCM materials melt with time and their temperature will raise. This phenomenon can reduce performance. As the velocity of the cooling fluid increases, the PCM material remains solid. In addition, the temperature of PCM and the output temperature of nanofluids increase with time. Wang et al. [138] have proposed a combination of PCM and liquid-based mini-channels for cooling of a rectangular battery pack. The PCM blocks are coupled between the batteries, and the liquid-based mini-channels were in contact with their lateral surface. They observed that this system improves battery cooling performance with acceptable mass and acceptable power consumption. At the discharge rate of 5C, this system decreases the maximum temperature from 64 °C to 46.3 °C, while a temperature difference of 2.52 °C is recorded. Cao et al. [139] proposed a combined thermal management system of liquid cooling and phase-change materials (PCM). The PCM material contains expanded graphite (EG)/RT44HC composites, and a cold plate containing circular channels is used in the middle of the cylindrical battery pack in contact with the PCM material. They found that the best water inlet temperature is 30 °C to achieve suitable performance. The use of EG-based composite PCMs with 67 mass% RT44HC can reduce the maximum temperature of the planar direction of the battery pack from 50 °C to 42 °C and from 5 °C to 1.2 °C, respectively. The planar temperature difference is the difference between the maximum and minimum temperatures on the top and middle surfaces of the battery.

In a prismatic battery module, Liu et al. [140] used a combination of composite phase-change material (CPCM) and liquid cooling to cool the system. A PCM block is used between the two consecutive battery cells, and inside each block, four rows of circular tubes containing cooling water are used. Experimental results showed that the performance of the hybrid cooling system is much better than pure CPCM. Also, increasing the flow rate and decreasing the inlet temperature are among the factors that change the cooling performance of the system. Under the 3C discharge−1C charge test, the inlet flow rate of 36 L min^{-1}, and the inlet temperature of 17 °C, the maximum temperature and temperature difference of the battery pack can be reduced to 44.5 °C and less than 5 °C, respectively.

Yang et al. [141] designed a combined heat management system of liquid–air mini-channels and airflow to cool the cylindrical battery module. In this system, the liquid flows through the corrugated channels and is in contact with the battery surface using a spacer. The airflow also flows parallel to the liquid channels using a fan inside a chamber that contains battery cells. Their results showed that the use of liquid-containing mini-channels and its combination with a spacer can reduce the maximum temperature to 304.98 K and the temperature difference to 4.13 K. Achieving such a temperature requires an inlet flow rate of 3×10^{-4} kg s^{-1}, which increases power consumption. Forced airflow along the batteries has a significant effect on the performance of the hybrid system. Inlet air at a speed of 4 ms^{-1} can reduce the maximum temperature and temperature difference by 2.22 K and 2.04 K, respectively, compared to static air.

Combining the indirect liquid cooling system with the heat pipe forms a high-performance heat management system so that the heat pipe is not immersed in the liquid. By adjusting the cooling flow to increase the temperature uniformity, a continuous cooling system for the battery can be achieved by using a combination of liquid and heat pipe systems [142]. Jang et al. [143] designed a combination of mini-channels heat sinks and heat pipes. In their design, the mini-channels heat sinks are in contact with the upper surface and the heat pipe is in contact with the lateral surface of the prismatic battery. The lower part of the heat pipes receives the heat of the battery, and in the upper part, the heat is dissipated by the liquid mini-channels. Combining a liquid cooling system with a heat pipe increases the heat transfer surface and therefore has a much higher performance than a conventional liquid cooling system. Under optimal conditions, the combined mini-channel and B-type heat pipe system (with a ring-like structure) reduce the maximum temperature of the battery module by 9.4 °C compared to the case of mini-channels without a heat pipe.

Conclusions and suggestions

In recent years, the high potential of lithium-ion batteries has been proven as a source of energy storage. One of the most important challenges in the application of these batteries is the temperature rise during operation. The studies on the use of micro-/mini-channels in battery thermal management systems and the factors affecting the performance improvement of these systems were reviewed. Finally, the most important results of this study were obtained as follows:

1. A significant challenge with liquid channel cooling is the complexity of their design, which enhances cost and size, and the possibility of leakage. In addition, a pump is required to circulate the fluid, which requires more space and additional energy. Compared to using water for cooling, ethylene, glycol, and nanofluids are more effective options.
2. The width and number of channels are among the factors affecting the cooling performance in the thermal management of rectangular batteries. Increasing the number of channels makes the temperature distribution more uniform, and increasing the width of the channels records the temperature decrease at a lower pressure drop. The use of channels with a suitable branch angle reduces the system pressure drop and consequently the pumping power while maintaining the cooling performance.
3. The counterflow gives a more uniform temperature distribution than the parallel flow in straight channels. However, it is different in U-turn channels and depends on both the number of channels and the flow pattern. Proper channel path and flow configuration keep the maximum temperature of the battery within a safe temperature range of 25°C $< T_{max} <$ 40°C. It can be seen that using the counter-flow configuration keeps the temperature difference within the $\Delta T <$ 5°C range. It was observed that the greatest effect on the cooling performance of the channels in the single-inlet case is for channel width > number of channels > channel inlet angle.
4. For cylindrical batteries, the contact angle of the battery with the cooling channels has the greatest impact on system performance. For this reason, corrugated channels or solid blocks are used to increase the contact angle between the battery and the cooling system. A proper contact surface not only decreases the temperature of the battery but also makes the temperature distribution in the battery pack more uniform. The use of double-layer channels reduces the maximum surface temperature of the cylindrical battery by 27.59% compared to single-layer channels. In cooling systems for cylindrical batteries, the greatest impact on cooling performance is related to contact angle > inlet velocity > number of channels.
5. The combination of mini-channels with phase-change material (PCM) can create a more uniform temperature distribution on the battery surface. Further, by filling the empty spaces between the cells with PCM, in addition to preventing heat escape, more heat is transferred from the batteries to the cooling channels, which raises the cooling performance. In addition, the combination of cooling channels with cross-forced airflow augments performance of the thermal management system with very little increase in system mass. Due to the high heat transfer rate in the heat pipes, the combination of the heat pipe and liquid channels without taking up much space has a high cooling performance to dissipate heat from lithium-ion batteries. Finally, it is found that combining other methods of battery heat management with liquid-based cooling channels reduces the temperature and improves its uniformity in the batteries.

Challenges and future works

Designing a thermal management system based on forced liquid cooling, in addition to proper cooling performance, should also be cost-effective in terms of pressure drop and pumping power. The mass of the system is also another important parameter that should be considered. Due to these factors, the use of superhydrophobic surfaces, in a way that maintains the cooling performance, can reduce the pressure drop of thermal management systems based on the liquid channels. The use of these surfaces has not been considered in battery thermal management systems and is suggested for future studies. In addition, using the porous sidewalls, due to their high surface-to-volume ratio, increases the heat transfer rate. On the other hand, at the interface between the fluid flow and the porous layer, the flow slips and compensates for the pressure drop partially. Flow mixing by a deflector can also be investigated in future studies if the increase in heat transfer rate is greater than the increase in pressure drop.

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