

A review on thermal management of battery packs for electric vehicles

Angelo Maiorino^{*}, Claudio Cilenti, Fabio Petruzzello, Ciro Aprea

Department of Industrial Engineering, University of Salerno, Via Giovanni Paolo II, 132, 84084 Fisciano, Salerno, Italy

ARTICLE INFO

Keywords:

Battery thermal management
Electric vehicles
Hybrid vehicles
Batteries
Temperature uniformity
Thermal runaway

ABSTRACT

The development of efficient *Electric Vehicles (EVs)* is related to the management of different parts of the powertrain, as the *Lithium-ion (Li-ion)* batteries. An important feature which affects their safety, performance, and useful life is the average temperature which must be included in an optimal range to prevent several dangerous phenomena. For this reason, *Thermal Management Systems (TMSs)* of battery packs of EVs are necessary to guarantee correct functioning in all environments and operating conditions. This review has the intention to divulge the recent developments in the thermal management of Li-ion batteries of EVs reached by researchers and car manufacturers to compare academic studies to the state of the art of the automotive industry from a thermal engineering point of view. Several experimental and numerical studies published in literature have been reported, and nine EV models have been analysed to explain how car manufacturers have developed their new models launched on the market. The choice of the models has been made since the quantity and the quality of data available on the official sites of manufacturers and specialist journals. In conclusion, the future perspectives of thermal management of battery packs are resumed to understand which path research and car manufacturers are following for the next generation of EVs.

1. Introduction

Nowadays, one of the greatest challenges related to the energetic field is the reduction of greenhouse gas emissions. Especially in the automotive industry, sustainability is one of the most important challenges that engineers must overcome, and *Electric Vehicles (EVs)* are considered by several countries in the world as one of the most promising solutions. Indeed, a strong standpoint is represented by the choice taken in 2022 by the European Union, according to which there will be a ban on the sale of new petrol and diesel vehicles from 2035. As decided through the released amendment, only electric cars and vans will be sold in each country of Europe to achieve the emission reduction targets for 2030 at 55 % for cars and 50 % for vans [1]. To be thorough, it is important to remember that achieving these goals is not related only to the substitution of conventional vehicles and transports but also to the fuel mix of each country. Indeed, the electric energy picked up from the grid by the EVs during the charging phase is associated with indirect emissions of pollutants related to the primary sources used for its production. Therefore, the effective advantage of EVs will be more relevant in countries where the percentage of fossil fuels is reduced to the minimum. For this reason, engineers and researchers must be focused not only on the development of new technologies for EVs but also on the

improvement of the energetic mixes, reducing the dependence on fossil fuels.

Lithium-ion (Li-ion) batteries have become the dominant technology for the automotive industry due to some unique features like high power and energy density, excellent storage capabilities and memory-free recharge characteristics. Unfortunately, there are several thermal disadvantages. For instance, under discharge conditions, a great amount of heat is generated by the redox reactions, and the battery temperature excessively rises [2]. Consequently, it is necessary to develop a battery cooling system to prevent cell damage due to high operative temperature. Moreover, other issues manifest when Li-ion batteries reach a lower temperature than optimum values, such as the incapability to withdraw energy or evident degradation. For this reason, a system able to warm up the device to achieve the correct temperature range is required. The technology responsible for warming up and cooling down the battery pack of an EV is called *Thermal Management System (TMS)*.

This review intends to report evolutions of the thermal management of battery packs of EVs achieved by research and car manufacturers in the last few years. The main purpose is to compare novel academic studies to the state of the art of the automotive industry from a thermal engineering point of view. The first part of the paper contains a brief outlook on battery technology and its modality of discharge and charge.

^{*} Corresponding author.

E-mail addresses: amaior@unisa.it (A. Maiorino), ccilenti@unisa.it (C. Cilenti), fpetruzzello@unisa.it (F. Petruzzello), aprea@unisa.it (C. Aprea).

In the second part, the problem of the thermal management of battery packs is considered, and the most interesting TMSs of battery packs are delineated. For each technique, recent numerical and experimental analyses are divulged to highlight which are the last progresses in this field. Regarding a further dissertation on the models used for the thermal management of batteries, the authors refer to a recent review article by Hafiz Muhammad Ali in which several theoretical modelling approaches are discussed [3]. After comparing these systems, it is presented a description of the concrete TMS of nine EVs launched on the market from 2018 in which technical data published on the official sites of manufacturers and specialistic journals are reported. In the final paragraph, the challenges, and the future direction of the TMSs technology are discussed to underline in which area of expertise research and the automotive industry are proceeding.

2. Essential characteristics of batteries

2.1. Outlook of battery technology

Batteries are devices which can convert the chemical energy contained in their active material into electric energy directly through oxidation and reduction reactions [2]. Usually, they are classified into two categories:

- *Primary batteries*: they cannot be recharged after the first application, and their life ends when all the chemical energy is converted into electric energy and wasted heat;
- *Secondary batteries (or rechargeable batteries)*: they can be recharged multiple times and are used as storage of electric energy. Therefore, secondary batteries are used in EVs for stocking and picking up energy from the electric grid.

Both primary and secondary batteries are formed by single cells connected in series and parallel to reach the desired nominal power, voltage and current. During the normal operation, two major phases appear:

- *Discharging phase*: it happens in both primary and secondary batteries. The device powers an electric load, and the chemical energy contained in the active material is converted into electric energy;
- *Charging phase*: it happens only in secondary batteries. The device is connected to a power generator (or the electric grid), and the input electric energy is converted into chemical energy and stored in the active material.

In the technical analysis of batteries, there are main characteristics, defined by typical values of voltage, current and capacity, which help to understand how the device works under specific conditions. In this part, the authors intend to recall several parameters which describe how batteries are designed and tested:

- *Nominal Capacity*: it is defined as the maximum charge that can be stocked in the battery and expressed in amper-hours (Ah). The nominal capacity is specified in fixed conditions because it is not a constant value. It is represented through the symbol C_x in which x is the discharge time in hours [2];
- *C-rate*: C-rate is computed as the current (charge or discharge, Amperes) divided by the nominal capacity (Ampere-hours) and is the inverse of the time required to charge or discharge the battery. This parameter indicates the speed of charging or discharging the cell for its maximum capacity [4]. For instance, a 20 Ah battery would provide 20 A for 1 h if it is discharged at a 1C rate, but the same battery discharged at 0.5C would provide 10 A for 2 h;
- *Nominal voltage*: it is defined as the reference battery voltage valued in nominal conditions and reported by the manufacturers;

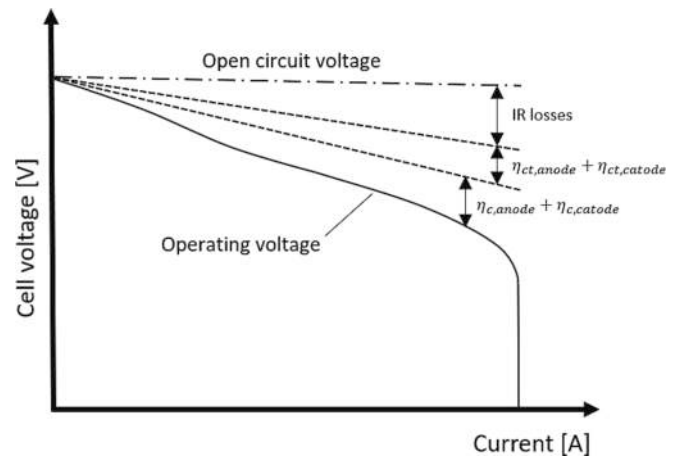


Fig. 1. Typical polarization curve of a battery cell [4].

- *Open circuit voltage (OCV)*: the OCV is the voltage the battery produces when no current flows in the electric circuit. In this condition, no reaction occurs inside the battery, and no energy is drained from the device;
- *Terminal voltage*: it is defined as the voltage between the battery terminals when an electric load is applied to the circuit during the discharging phase [2]. It is not constant and follows a specific curve called the *discharge curve*;
- *Cut-off voltage*: it is the minimum allowable voltage, and it is the value that defines the empty state of the battery;
- *Charge voltage*: it is the instantaneous voltage measured during the charging phase. This parameter assumes values which follow a defined *charging scheme*;

Due to the electrochemical losses caused by the irreversibility of the reduction and oxidation reactions, the terminal voltage of a cell is not equal to the theoretical maximum voltage the which device can supply. *Polarization losses* influence the expression of the terminal voltage of a battery as follows [4]:

$$E = E_0 - (\eta_{ct,anode} + \eta_{ct,cathode}) - (\eta_{c,anode} + \eta_{c,cathode}) - iR_i = iR_{load} \quad (1)$$

E_0 is the OCV, $\eta_{ct,i}$ is the *activation loss voltage drop* of each electrode, $\eta_{c,i}$ is the *concentration loss voltage drop* of each electrode and iR_i is the *ohmic loss voltage drop* due to the internal resistance of the battery cell. Every loss increases when the current intensity rises as shown in Fig. 1.

This curve is called the *polarization curve* of the cell and describes how the terminal voltage of a single cell decreases from the OCV due to the polarization losses for each value of current produced by the device.

From an energetic perspective, polarization losses cause degradation of the chemical energy stored in batteries. In fact, due to all the irreversible phenomena which affect the main components (anode, cathode, electrolyte, and electrical connections), these devices produce the required electric energy but also wasted heat which must be removed. To preserve the battery from the decay of performance, the wasted heat must be removed through an appropriate TMS.

2.2. Discharging and charging methods of batteries

The safety, durability and performance of batteries are also highly dependent on how they are discharged or charged. As reported in literature, there are three basic modes by which a battery can be discharged [4]:

- *Constant Resistance*: during the discharging phase, the battery is connected to an electric load. This load is characterised by an electric resistance which may be constant or variable. If the load resistance

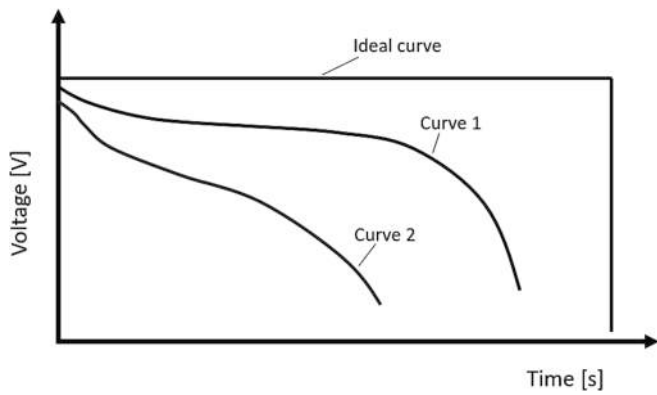


Fig. 2. Typical discharging curve of a battery [4].

does not change, the current will decrease proportionally to the battery voltage according to the polarization curve;

- *Constant Current*: in this case, the resistance load is variable during the discharging phase, and the voltage decreases. Despite that, the current remains the same and does not change;
- *Constant Power*: during this discharging mode, the current and the voltage are not constant, but their product (the electric power) remains the same and does not change.

For each discharging mode, the terminal voltage follows a typical path which defines the *discharge curve* of the battery [4]:

In Fig. 2 three different conditions are represented. In ideal conditions, there are no polarization losses, and the terminal voltage remains constant and equal to OCV. Then, when the battery is fully discharged, the terminal voltage drops to zero instantaneously. In real conditions, as described in the previous paragraph, the polarization losses produce voltage drops due to the activation, concentration and ohmic losses, and the terminal voltage decreases. This drop is more and more intense, and for this reason, the speed of decay grows during the time until the cut-off voltage is reached. Moreover, in Fig. 2, two real curves are reported. At the same conditions, the second curve is related to a higher value of the

internal resistance, which produces higher ohmic losses [4].

In a similar way, the charging phase is characterised by two main methods:

- *Constant voltage*: this method is probably the simplest charging scheme [2]. The battery charging current is not constant and decreases continuously during the process. The drawback of this method is the requirement of very high power in the early stage of charging [2];
- *Constant current*: in this case, the charge voltage is controlled to maintain a constant current to the battery. Generally, this condition is estimated utilizing controls of temperature or charge voltage rising during this phase [2].

A combination of these two methods is used for the batteries of the EVs powertrain. In Fig. 3 is represented a typical charging curve of a new Li-ion battery cell which is charged for the first time [2].

When the cell comes out from the production chain, it is pre-charged using a low constant current method [2] (in the figure, the pre-charging is characterised by a C rate equal to 0.1). Then, the charging phase is characterised by a constant current method in which the intensity of the current becomes much higher. It continues until the charge voltage reaches the *voltage upper limit* (in this case equal to 4.1 V) whose value is generally provided by the manufacturer. To be thorough, batteries are also characterized by a *voltage lower limit* (in this case 2.5 V) in which the device is not allowed to go below. After this condition, the constant voltage phase is defined, and the charging process is active until the battery is full. In Fig. 3, a re-charging section is represented: this is less than the first charging phase because it represents the EV *regenerative braking* [2] in which part of the kinetic energy is recovered and stocked in the battery pack. It would not be correct to consider only the charging phase through the connection to the grid because the battery pack of EVs are continuously charged and discharged when the vehicle breaks and then is in the throttle.

3. Thermal management systems of EVs battery pack

The thermal management systems of the EVs Li-ion batteries have a

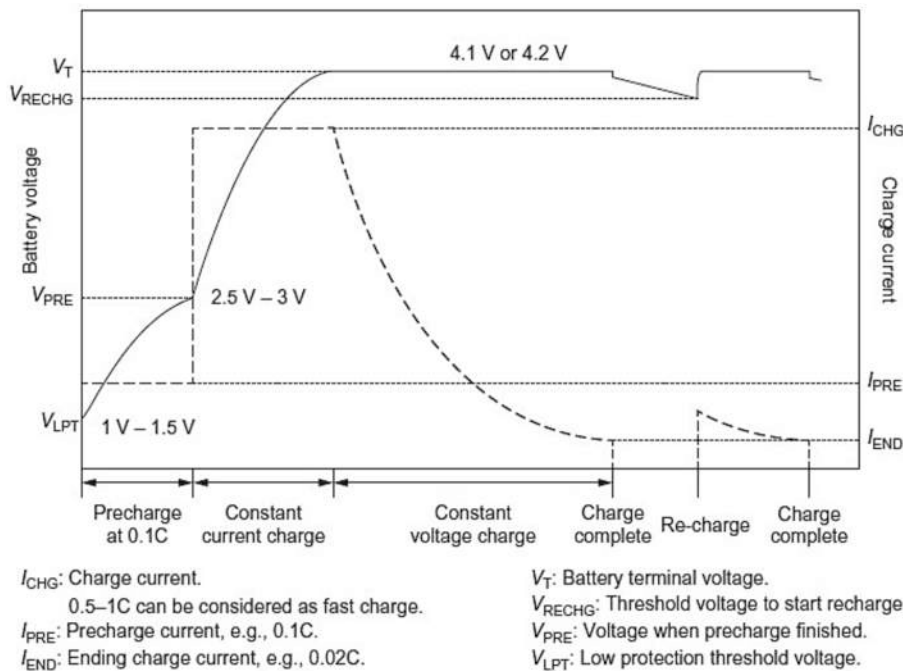


Fig. 3. Charge curve of an EV Li-ion battery cell [2].

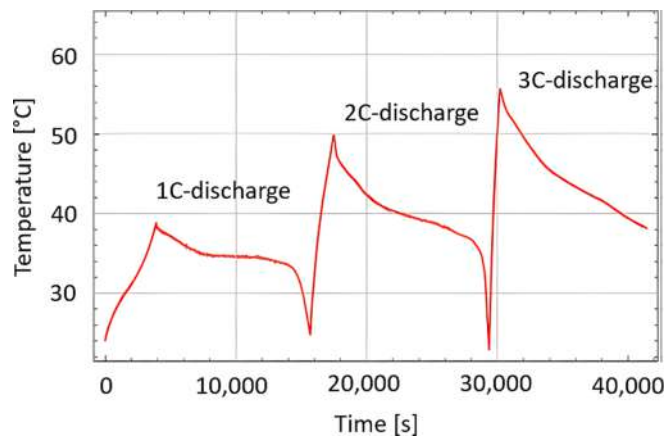


Fig. 4. Temperature rise of a Li-ion cell during charge and discharge cycles [2].

key role in the powertrain project to prevent several conditions which can affect the safety, performance, and degradation of the battery pack. There are ordinary and unordinary circumstances in which the average temperature of the battery pack can rise uncontrollably causing abnormal chemical changes, such as the electrolyte decomposition or reactions between the electrodes and the electrolyte. For instance, during normal charging and discharging cycles, the heat generated by the electrochemical losses and the electric resistances can increase the main temperature of the battery. Here are some numerical values reported by Koki Ogura et al. [2]. A 20 Ah battery is subjected to several discharging and charging phases in which three different C-rate are considered: 1C, 2C and 3C. These values correspond respectively to 20 A, 40 A and 60 A discharge, and the discharging times are equal to 1 h, 30 min and 20 min. As shown in Fig. 4, the temperature of the battery rises to values equal to 50 °C (for 2C) and 55 °C (for 3C).

Instead, an uncontrolled temperature rise can be provoked during unordinary working conditions by a phenomenon called *thermal runaway*. A thermal runaway consists of exothermic chain reactions within the battery that cause the inner structure to destabilise and degrade until a total failure of the device is complete [5]. This phenomenon can occur from various forms of mechanical, electrical, and thermal abuse, which produces a short circuit between the electrodes of the battery cell due to electrolyte failure. The heat generated affects the adjacent cells, which are subjected to the same occurrence. This chain reaction not only increases the battery pack temperature but releases many flammable gases, which increase the internal pressure of the pack and cause potential explosion and fire of the EV powertrain [5]. As reported by Peiyi Sun et al. [6], in 2018, more than fifteen fire accidents of various electric cars occurred due to the thermal runaway phenomenon, which is one of the most important safety issues of EVs to overcome. The causes of these explosions are various and happen in different conditions, such as driving, charging or parked cars. In other cases, the flame was produced after a collision, which affected the mechanical behaviours of the battery pack, causing in a second moment the explosion of the powertrain. The thermal runaway can also have a dangerous effect during natural catastrophes such as alluvions because the EVs becomes unusable due to safety reason. A recent example is the alluvion which hit the Italian region Emilia Romagna in May 2023. The flooded streets encouraged Ravenna to block EVs in lockdown for fifteen days due to safety reasons related to the possibility of major blazes and blasts [7].

As an uncontrolled rise of the average temperature affects the performance, an uncontrolled decrease of the battery temperature can reduce many key factors, such as the electrolyte conductivity and lithium diffusion, because it increases the electric and electrochemical losses. This is a big challenge for those countries in which the ambient temperature in winter often decreases under 0 °C (as China, Europe, and the United States). These difficulties are aggravated below -20 °C, in

which the power sourcing capabilities are limited [8]. Consequently, the heating process is more challenging than the cooling one because there could be environmental conditions in which the system cannot withdraw energy from the battery pack to activate the TMS [9]. Therefore, the warming-up phase is essential to prevent the phenomenon responsible for a decay of performance: the *lithium plating*. Lithium plating is the deposition of metallic lithium on the anode surface made by graphite surface under fast charging or low-temperature conditions [10]. It is responsible for reducing the battery life and its capability to stock and release energy during the charging/discharging cycle. Unfortunately, despite the numerous research done over the years, nowadays, the mechanism of formation is not fully detected [10].

Due to this consideration, it has been defined an optimal range in which the main temperature of a Li-ion battery must be included to reduce every phenomenon which affects the useful life, safety, and performance of the battery. According to the studies conducted by Pesaran et al. [11], Li-ion battery packs of EVs do not manifest evident damage and degradation in an optimal range between 15 °C and 35 °C. Generally, the acceptable temperature region of Li-ion batteries is wider than this range and is defined between -20 °C and 60 °C [12]. Another characteristic is related to the internal temperature of the battery. It is important to manage the battery pack temperature field uniformly to avoid extreme variation between each cell, which can cause undesired internal heat exchanges. Usually, the temperature difference within the battery pack should not exceed 5 °C [13].

In the past few years, many TMSs have been developed, and several studies have been published in literature. The affirmed technologies developed during the years are the following:

- Air-based TMSs [14–21];
- Liquid-based TMSs [9,20,22,23];
- Refrigerant-based TMSs [20,21,24];
- Phase Change Materials (PCM) TMSs [20,25,26];
- Heat Pipes (HPs) TMSs [20,27].

The first three mentioned techniques are *active TMSs* because they require electric energy to operate, while the last two are *passive TMSs* because they do not require any electric energy source. The combination of at least two of these systems forms a *Hybrid Thermal Management System (HTMS)* in which at least two of these are included [20,28,29]. While these technologies can be used both as cooling and heating systems, the study of heating-only technology includes two possible strategies [8,30,31]:

- *External heating strategies*: the heat is generated by external sources which produce thermal energy *outside* the battery. These can be *electric heaters, heat pumps, electric motors or hardware components* (capacitors or inverters) [8,32,33]. The energy source of these machines can be the battery itself or the electric grid if the battery pack is not able to supply electric energy due to low ambient temperatures;
- *Internal heating strategies*: the battery impedance in cold weather generates a great amount of heat *inside* the cells, which self-increases the battery pack temperature.

When a current flows into the cells, the polarization losses generate heat and directly warm up the battery pack. The second cluster of techniques can increase the battery pack temperature from its internal part reducing the thermal energy dispersions to the environment and making a homogeneous temperature field quickly [8]. In literature, four main internal heating strategies can be found:

- Internal self-heating [8,34];
- Mutual pulse heating [8,35];
- Self-Heating Lithium-ion Battery (SHLB) [8,36,37];
- Alternating current heating [8,20,32,33].

Table 1
Comparison of the TMSs used for the EV battery packs.

TMS	Type	Advantages	Disadvantages	References
Air	External heating/cooling	<ul style="list-style-type: none"> • High reliability • Low cost • Simply maintenance 	<ul style="list-style-type: none"> • Low efficiency • Dust and pollutants in the ducts 	[14–21]
Liquid	External heating/cooling	<ul style="list-style-type: none"> • High efficiency of the heat exchange • Low energy demand 	<ul style="list-style-type: none"> • High number of components • High cost of installation and maintenance 	[9,20,22,23]
Refrigerant	External heating/cooling	<ul style="list-style-type: none"> • Best efficiency of the heat exchange • Low impact on the weight of the vehicle 	<ul style="list-style-type: none"> • High complexity of the plant • Not always the inverse machine can be reversible 	[20,21,24]
PCM	External heating/cooling	<ul style="list-style-type: none"> • Fixed temperature during the phase change • Do not require additional electric power 	<ul style="list-style-type: none"> • Low thermal conductivity, which does not allow heat dissipation during the cooling down • The addition of conductive materials may produce fires 	[20,25,26]
Heat Pipes	External heating/cooling	<ul style="list-style-type: none"> • Do not require any additional electric power • Low maintenance • High thermal conductivity 	<ul style="list-style-type: none"> • Small contact area • Thermal management is not always reached • No stand-alone applications 	[20,27]
Internal Strategies	Internal heating only	<ul style="list-style-type: none"> • High heating efficiency • High heating rates • Good temperature uniformity 	<ul style="list-style-type: none"> • AC preheating needs an external energy source • High degradation of the battery pack due to the formation of Li-ion plating 	[8,20,32–37]

In the next paragraphs, recent numerical and experimental studies about these TMSs will be reported. Furthermore, the first five systems will be analysed as cooling and heating systems to offer a general perspective of the applications in every climate condition. For further information, a comparison among these technologies has been reported in Table 1.

3.1. Air-based TMSs

Air-based TMSs are widely used in EVs because they have a simple structure, high reliability, low cost, and simple maintenance [38]. These characteristics are achieved by a simple plant layout requiring less equipment than other techniques [39]. The main feature of air-based TMSs is using air as a working fluid. One of the advantages in terms of the safety and environmental impact of these systems is that air is available at any moment and is not toxic or inflammable [40]. There are several classifications of these systems regarding how air flows through the pipe network and how it is treated to achieve the desired temperature of the battery pack. The first distinction is between:

- *Forced convection systems*: the airflow in the circuit is generated by an electric fan. This system requires a specific amount of electric energy due to the demand of the electric motor of the fan;

- *Natural convection systems*: the airflow is supplied through the vehicle motion, and no fan is required. To reduce air pressure drops, the design of ducts and shapes is crucial [15].

The second distinction regards how air is treated through different plant layouts [14,20]:

- *Passive technique*: the air is taken directly from the atmosphere and is heated or cooled by a heat exchanger. In some configurations, the flow may also be mixed with part of the exhausted air taken from the circuit outlet. Then, the air is conducted in the battery pack for the thermal management;

- *Active technique*: part of the exhausted air is brought to the inlet and mixed with new fluid from the atmosphere. Then, the heat exchanger cools down or heats the fluid to reach the optimal temperature for battery pack management.

Related to these classifications, two layouts of air-based TMSs can be used. These are represented in Fig. 5.

These plants can be used both as cooling and heating systems. In fact, during the cooling down phase, there is a cold coil (evaporator core) in which air temperature decreases using the evaporator of the HVAC system of the vehicle. Otherwise, if the battery pack needs to be warmed up, the hot coil (heater core) permits to increase the temperature of the

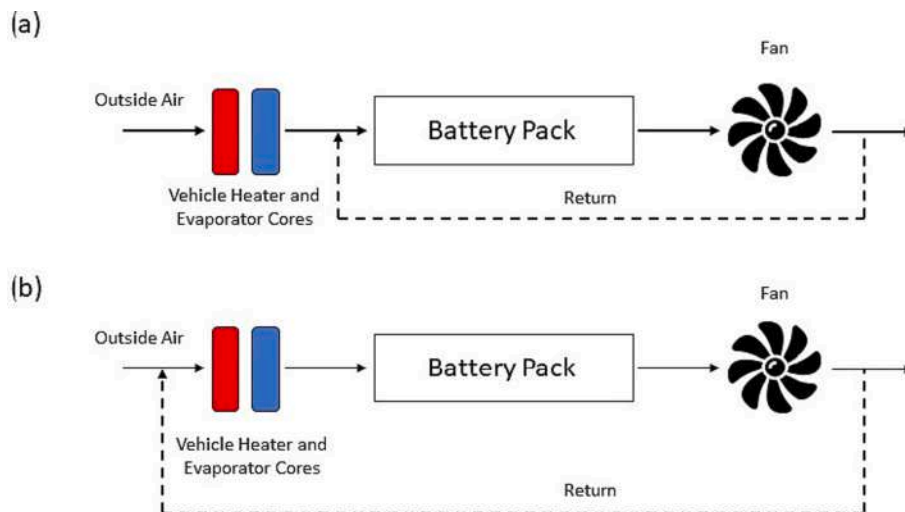


Fig. 5. (a) Passive air cooling/heating system, (b) Active air cooling/heating system [20].

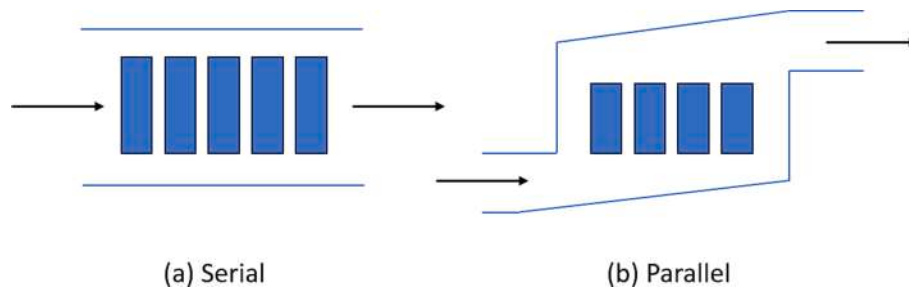


Fig. 6. (a) Serial duct for air-based TMSs (b) Parallel duct for air-based TMSs [13].

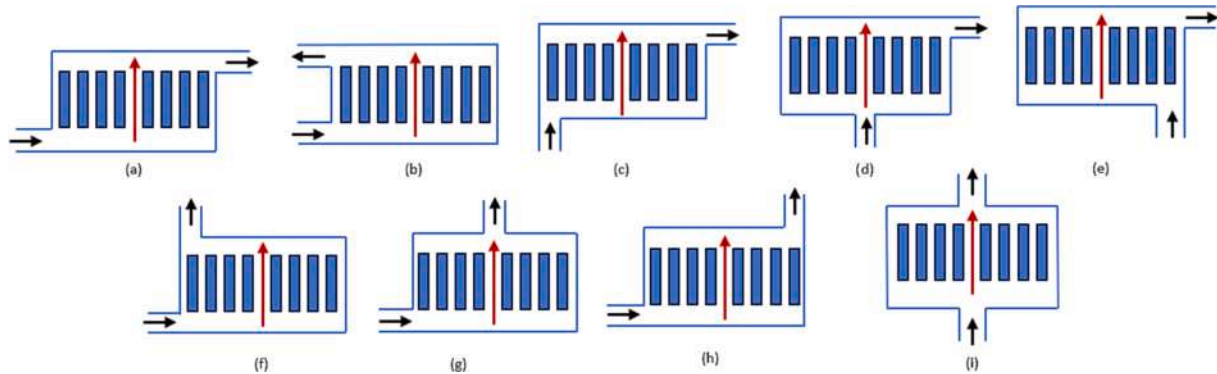


Fig. 7. Various ducts shapes used for air-based TMSs [20].

inlet flow of air directed to the battery pack. It is interesting to highlight the difference between passive and active techniques. In layout (a) the heat exchanger is positioned before the air recycle while in layout (b) the heat exchanger is positioned after the air recycle. Moreover, the pipe network is generally open, and the possibility of using natural convection may bring the advantage of eliminating any fan and decreasing the vehicle energy demand [38].

However, there are weaknesses which affect the air-based TMSs. One of these is the lower efficiency than other systems because the heat exchange between the battery pack and air is ineffective. The specific capacity and the thermal conductivity of air are lower than other fluids (for example liquids), and this causes a decrement of the convective heat exchange coefficient. Moreover, despite other systems having the necessity of pumps, the fans for air-forced convection require a higher amount of energy [39] due to the higher specific volume than other liquid fluids at the same conditions. The last issue is related to the source of the working fluid. The environment brings air in which dust or other pollutants are transported into the circuit causing an interference with the heat exchange. This phenomenon decreases the battery pack TMS performance [39].

Another fundamental matter of air-based TMSs is the design of the air duct shapes. Generally, a distinction is made between *serial ducts* and *parallel ducts* [13]. In serial ducts, the airflow direction is perpendicular to the major surface of the battery, while in parallel ducts the flow direction is parallel to them. The scheme of these two configurations is represented in Fig. 6.

This first difference is an incipit to define various shapes of ducts, as shown in Fig. 7.

Many other innovative duct shapes have been proposed for improving the convective heat exchange between air and batteries. Xueyanh Shen et al. [17] have developed a modified Z-shaped system in which the rotation angle of each cell is not null. As represented in Fig. 6 and Fig. 7, the angle between the air channels and the batteries equals 0° and a perpendicular flow is made. In this innovative shape, the angle between the battery cells and the inlet and outlet duct is not null and different inclinations were tested for the best configuration. The

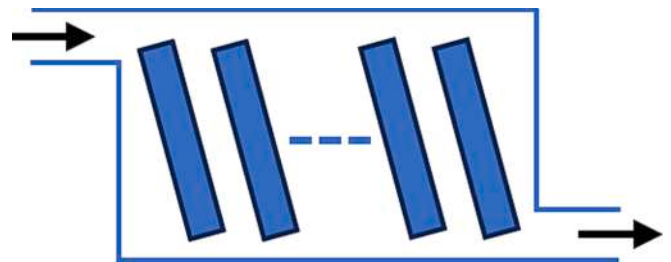


Fig. 8. Modified Z-shape proposed by X. Shen et al. [17].

temperature field reached through the numerical analysis is represented in Fig. 8.

Interestingly, a minimum change in shape can produce relevant results. According to the numerical analysis of Xueyanh Shen et al., the maximum temperature and the maximum temperature difference of the battery pack are 36.9°C and 2.4°C and are decreased by 3.4 % and 5.8 % than traditional Z-shaped ducts. The optimal angle the analysis finds is equal to 19° [17].

Another innovative shape is a new U-shaped duct air-based TMS proposed by Zhi Xu et al. [18]. They have developed a numerical simulation of the U-shaped system with various inlet positions and airspeed. The authors have observed that the modified U-shape can decrease the maximum temperature by 4.2°C only by changing the inlet position. Another important result is obtaining a speed gain from 2 m/s to 5 m/s, achieving a battery pack temperature reduction from 8.5°C to 18.5°C [18].

The Z-shaped and U-shaped air-based systems are not the only shapes proposed in the literature. Furen Zhang et al. [19] have developed a T-shaped system which can be considered as a union between the Z-type and U-type. According to their numerical analysis, the proposed system reduced the maximum temperature and the maximum temperature difference by 2.2 % and 90.8 %, respectively. This duct is represented in Fig. 9.

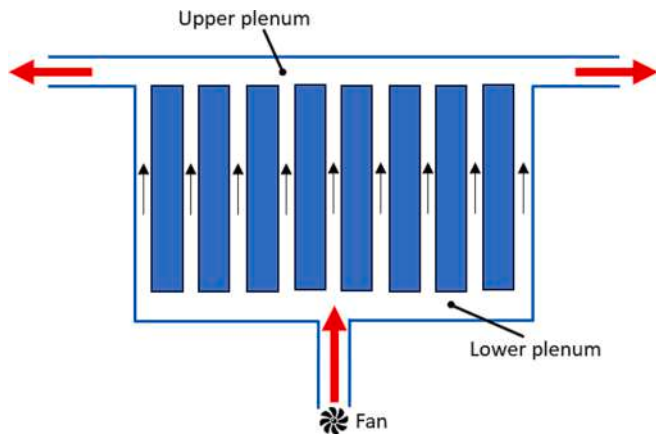


Fig. 9. T-shaped air-cooling system proposed by Furen Zhang et al. [19].

Other approaches regarding air-based TMSs development can be found in literature. Still, there are only a few applications in which this technology is designed both as heating and cooling system. One of these is a novel TMS developed by Xiaobin Xu et al. [41] who have implemented an air-cooling system with two heaters composed of polyamide films and nickel sheets. These layers are attached on the upper and bottom surface of a *Sleeved Heat Spreader Plate (SHSP)*, which is a sleeved structure with a large heat exchange conductive area used to pre-heat and cool the battery cells. The experimental setup is formed by 20Li-ion cells orthogonal arranged which guarantee a nominal capacity and a nominal voltage equal to 12.5 Ah and 14.4 V connected in 5P4S (5 in parallel and 4 in serial) by nickel sheets through spot welding. In cooling mode, considering an ambient temperature of 25 °C, a discharge rate of 3C and an inlet air velocity equal to 1 m/s, the temperature increment and temperature difference are respectively only 12.9 °C and 2.8 °C. Regarding heating mode tests, considering an environmental temperature equal to - 20 °C, the heating rate and efficiency achieved by this novel system are 7.0 °C/min and 69.8 %. These results are promising because the reported values are higher than the existing external heating strategies and comparable to the performances of internal heating strategies without any degradation of the Li-ion cells [41].

3.2. Liquid-based TMSs

The liquid-based TMSs are very similar to the air-based ones except for the coolant, which is a liquid substance such as water and glycol mixtures [9] or dielectric fluids. Compared to air-based TMSs, the liquid-based technology is more efficient because achieves a better heat exchange and requires a lower electric energy demand from the battery pack. In fact, due to the better thermal properties (such as thermal conductivity and specific heat) and the higher density under the same conditions, the convective heat exchange is improved, and the mass flow

rate at the same flow speed and duct geometry is higher [39]. Regarding the system layout, liquid-based TMSs are characterized by a closed circuit in which the fluid is confined. It is represented in Fig. 10.

The layout of a liquid-based TMS has more components than air-based. Indeed, compared to the previous layouts, it is formed by a pump, which is necessary to generate a mass flow, and an expansion tank for managing the volume variations caused by the ambient temperature fluctuations. As mentioned before, a liquid-based system can be used both as a cooling down or warming up system through a single halfway heat exchanger which can be used as a cooler or heater [42]. Generally, the HVAC system of the vehicle is the source of thermal or cooling energy by means of a four-way valve that can switch the functioning from a refrigerator to a heat pump mode [38]. In some applications for cold weather, the wasted heat produced by the electric motor can be transferred to the liquid utilizing another halfway heat exchanger to recover part of the thermal energy dissipated to the ambient [9].

On the other hand, the complexity of the layout, due to the higher number of components, is one of the disadvantages of liquid-based systems. This issue increases the weight of the vehicle and the occupied volume of the battery pack. For this reason, the installation cost is higher than the other solutions and its maintenance operations increase [39].

Regarding how the working fluid interacts with the surface of batteries, the liquid-based TMSs are classified into three categories:

- *Immersive heat exchange*: the battery pack cells are completely immersed in a dielectric fluid. This solution brings many advantages as high heat transfer and thermal stability, but the most important effect is the ability to maintain a uniform temperature field among the cells [9];
- *Direct heat exchange*: the surface of the battery pack is in direct contact with the working fluid, but the single conductive parts are not involved. The main advantages are the same as the immersive cooling, but the heat exchange is achieved only between the liquid and the external surface of the Li-ion cells. The main disadvantage is the additional thermal resistance of the external case [9];
- *Indirect heat exchange*: the heat exchange is realised using an interface between the battery pack surface and the liquid fluid. This interface can be a cooling plate, distinct piping, or jackets. Compared to the other heat exchanges, there is no limit to the fluid choice because the electrical parts of the battery pack are isolated and there is no risk of short circuit. This system is also less expensive than the previous two because it can be characterised by a cheaper working fluid, fewer accessories, and maintenance.

In literature, novel experimental and numerical analysis has been proposed regarding these heat exchange techniques. One of these has been developed by M. Larrañaga et al. [22] who proposed a novel direct liquid cooling strategy for the EVs battery pack. It uses a dielectric fluid which flows through U-shape channels made in the shells of the battery

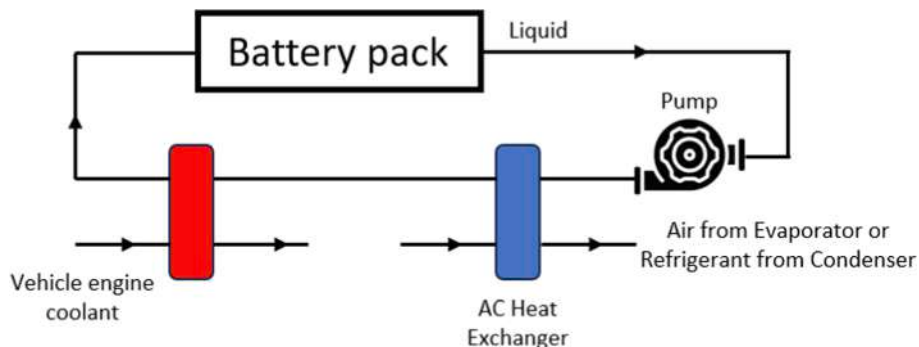


Fig. 10. Liquid cooling/heating system [42].

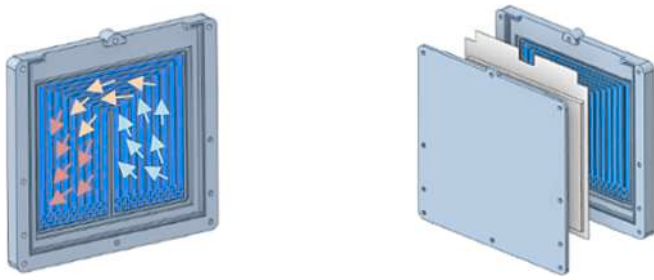


Fig. 11. U-shape channels developed by M. Larrañaga et al. [22].

cells as represented in Fig. 11.

This numerical and experimental study also considers the energetic demand by the pump through the estimation of pressure drops and how the TMSs control the maximum temperature and temperature differences between the cells. Considering a constant flow of 0.43 L/min at steady state, the reference battery (a nickel-manganese-cobalt one) has achieved a maximum temperature near 30 °C. This is a desired result because the value is included in the previously defined optimal range. Moreover, the temperature field homogeneity has been reached: in fact, the maximum temperature difference between the cells has been estimated equal to 0.4 °C. A comparison between the direct liquid cooling system and an indirect one is made under the same working conditions. The researchers have demonstrated the indirect strategy has a lower efficiency because the tested battery pack has reached a maximum temperature of 38.9 °C and a difference between the cells equal to 5.7 °C. M. Larrañaga et al. [22] have shown that even though the indirect liquid cooling systems are less complex regarding the plant accessories and management, the battery pack thermal management does not achieve the same results.

An example of indirect liquid cooling is the system developed by Ping He et al. [23] which uses a novel I-shaped channel cooling plate exchanger applied to a 40 Ah Li-ion battery. According to this numerical study, at a steady state, this system can decrease the maximum temperature from 33.9 °C to 30.8 °C. As in other studies, the system improvement is based on the flow channel structure and design of the cooling plate for reducing the circuit pressure drop and maximising the convective heat exchange. The developed liquid cooling plate is a double-layered I-shaped channel whose structure has been inspired by fractal structures in bionics. In Fig. 12 it is represented the 3D model of ducts and the cooling plate developed by Ping He et al. [23].

Three designs were studied, and the most effective was chosen for the experimental test. This plate is defined as “double-layered” because the inlet liquid enters the top channel and interacts with the cells by means of the halfway metallic slab. The returning circuit is put under the inlet one and is the second layer represented in blue in Fig. 12. According to the researchers, this multichannel device improves the thermal conductivity, improving the heat exchange and reducing the battery pack cooling time.

Other studies have been conducted regarding the optimal shape of the liquid channels to improve the heat exchange between the working fluid and the battery pack. Wei Zuo et al. [43] proposed two mini U-channel cold plates to cling to the front and back surfaces of a prismatic Li-ion battery to reduce the maximum temperature reached by the cells. According to the numerical analysis, the maximum temperature of the battery is reduced to about 38.7 °C under cooling plans at the inlet velocity of 0.01 m/s and for a discharge rate of 1C. Another article developed by Wei Zuo et al. [44] reports a numerical analysis of a comparison between a single S-channel and double S-channel cold plate for thermal management of a prismatic Li-ion battery. The liquid used for this cooling system is a mixture of water and glycol, and the battery has a nominal capacity of 20 Ah. For three different discharge rates (3C, 4C and 5C), the results showed the maximum temperature difference inside the cells is lower for the double S-channel cold plate. In contrast, the maximum temperature reached is almost similar. An important result regards the reduction of pressure drops because this novel shape permits a reduction of the pumping power estimated to 73.88 %. Yuntian Zhang et al. [45] investigated the effects of an inclined channel cold plate compared to a straight channel cold plate for different coolants. Various parameters have been vaulted as the j/f factor which is defined as the ratio between the non-dimensional surface heat transfer and the surface friction factor. According to the numerical simulations, the performance of the cold plate is influenced by several characteristics, such as the coolant, the mass flow rate, the number of channels and the inclination angle. In particular, the efficiency of the system rises when the inclination angle is maximised. For example, the j/f factor is improved by 79.64 % for a mass flow of water equal to 0,6 g/s, the number of channels is 5, and the inclination angle is equal to 15°. A similar analysis was conducted by Wei Zuo et al. [46] who proposed an improved multi-channel cold plate for the thermal management of a prismatic Li-ion battery. They obtained the maximum j/f factor and the lowest pressure drop for a mass flow rate equal to 0.4 g/s, a number of channels equal to 5 and an oblique angle of the structure equal to 45°.

There are also cases in which the optimization of liquid-based TMSs

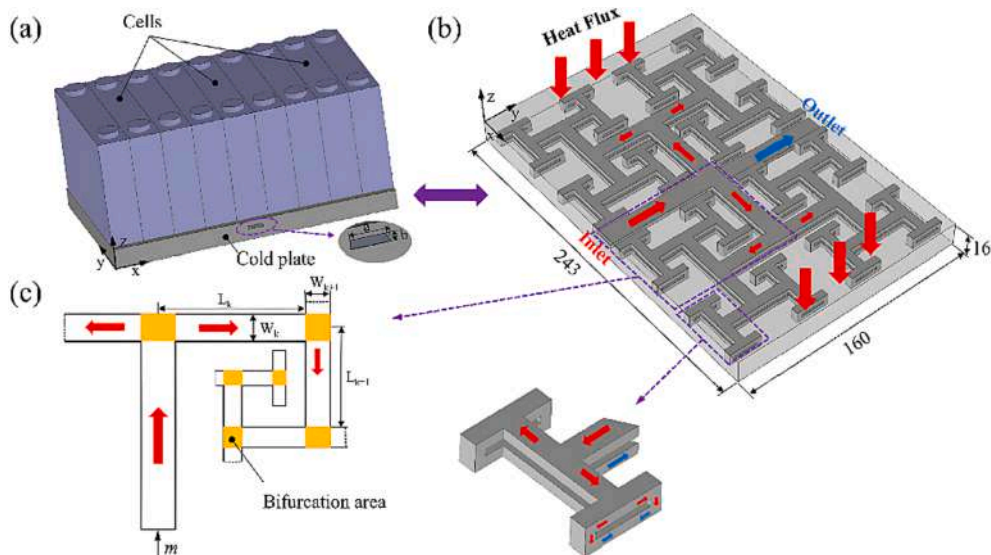


Fig. 12. I-shaped liquid cooling plate developed by Ping He et al. [23].

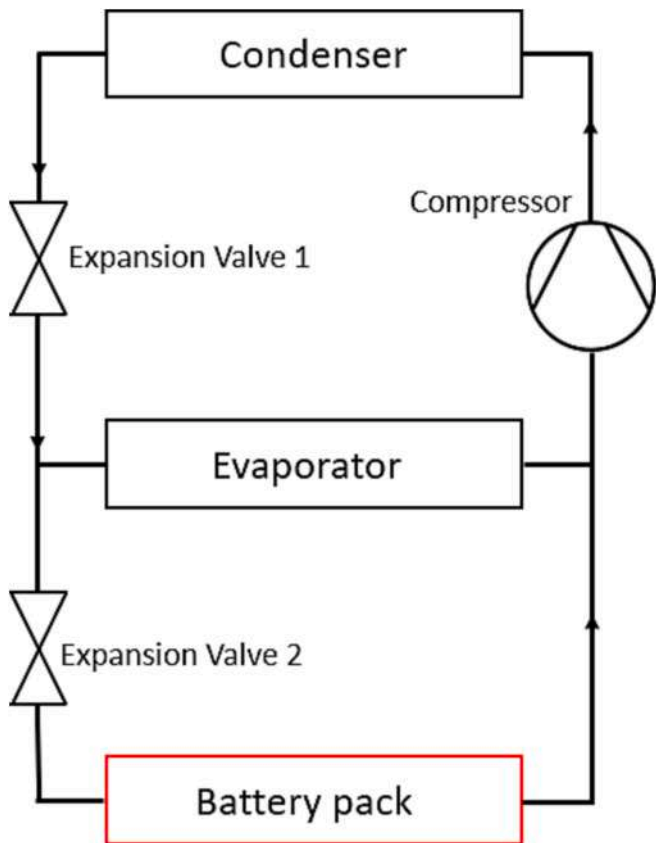


Fig. 13. Basic scheme of TMS based on compression vapour cycle [20].

is achieved using different mass flow strategies. For instance, Dexin Li et al. [47] investigated the effect of pulsating and steady flow on the heat exchange and energy consumption of a multi-channel cold plate. As shown by the results of this numerical analysis, the pulsating flow has positive and negative effects on the heat transfer, pressure loss and efficiency during the discharge process. Moreover, these effects depend on the pulsating frequency and amplitude. According to the authors, when a pulsating flow is considered, and its frequency and amplitude are respectively 3 Hz and 30 % of the velocity of the liquid at steady conditions, the energy consumption of the pump is 5.19 % lower than the steady flow case.

3.3. Refrigerant-based TMSs

In the last years, there have been studies which have focused their attention on the implementation of machines based on inverse cycles. In particular, the compression vapour cycles can be used to cool batteries by means of a dedicated evaporator, which has the role of decreasing the average temperature of the battery pack. The most important advantage achieved by these systems is the heat exchange efficiency. It is well known that the two-phase heat exchange reaches the highest convective heat transfer coefficient compared to liquids and gases and its processing temperature maintains a constant value. Moreover, the fixed temperature permits to control proper conditions for the Li-ion battery thermal management and obtaining a more uniform temperature field [39]. In literature, there are many examples in which the EV battery packs are cooled down by means of refrigerators [20,21,24]. These techniques generally use the vehicle HVAC system employing a heat exchanger positioned in parallel to the evaporator, as shown in Fig. 13.

Despite the represented layout is a typical refrigerant-based TMS, it must be more complex in normal applications. Indeed, this technique must be able not only to cool down but also to heat the battery pack independently from the conditioning of the vehicle cabin. Jian Guo et al. [24] have proposed a novel plant in which the TMS can cool down or heat up the battery pack by means of different pipe networks and valves.

In Fig. 14 (a) it is represented the heating up phase of the battery pack. The refrigerant comes out of the compressor and is directed to the powertrain batteries, which are warmed up. Meanwhile, the cabin is heated through a heat exchanger positioned at the compressor outlet. In Fig. 14 (b) it is represented the battery pack cooling down phase. It is realized by a pipe network which brings the refrigerant from the expansion valve to the battery while the cabin heating is made through the same heat exchanger. If the cabin must be cooled down, the second heat exchanger is positioned before the compressor, and the external heat exchanger works as a condenser. Indeed, the external heat exchanger can be used as a condenser or evaporator based on the air conditioning and battery pack heating or cooling combination, as shown in Fig. 14 (c). The main innovation achieved by Jian Guo et al. [24] is a precise battery pack and cabin temperature control by means of different expansion valves dedicated to each heat exchanger. This solution is very helpful for the independence of the powertrain batteries and the cabin temperatures, but it is a complex proposal due to the articulated layout.

Another important topic related to refrigerant-based TMSs is refrigerant choice. There are many studies in literature in which different refrigerants used in HVAC and TMSs of EV batteries are compared. This overview is important because the refrigerant influences the TMS performance, which is linked to EV energy consumption. Jing Wu et al. [21]

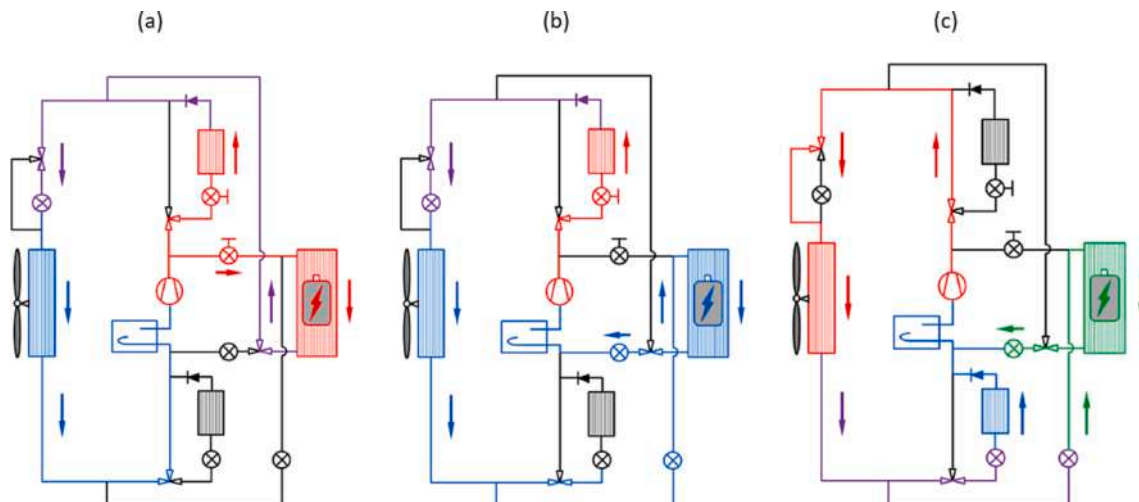


Fig. 14. Refrigerant-base TMS layout developed by Jian Guo et al. [24].

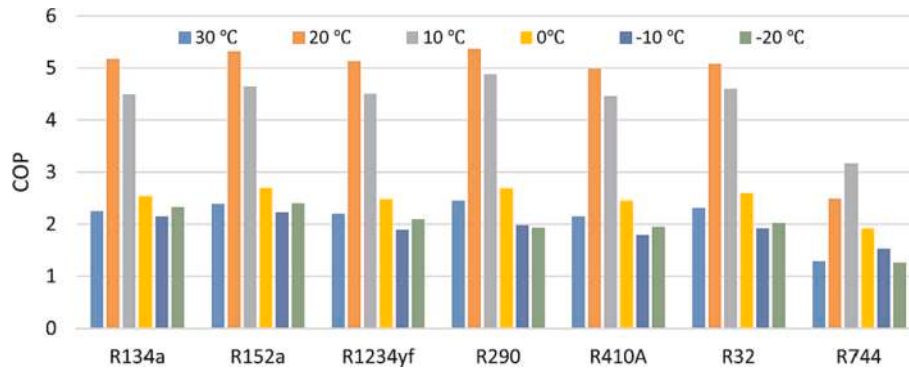


Fig. 15. Refrigerant used for electric vehicles HVAC systems and TMSs [21].

have compared different refrigerants used in EVs air conditioning systems and powertrain batteries TMSs and have numerically estimated the COP as refrigerator and heat pump assuming a cabin temperature of 24 °C and different values of the ambient temperature. Seven refrigerant substitutes of R134a at six ambient temperatures were compared numerically, considering a Rankine inverse cycle without any internal heat exchanger. These results are represented in Fig. 15 [21].

All the values calculated are similar, and R290 and R152a reach the best TMS performance. Instead, R744 (CO₂) achieves a lower COP in all ambient conditions. In literature, there are applications in which R744 is used as a refrigerant, but they are not as numerous. Today the most used fluids are the R123a or R1234yf due to the low environmental impact and optimal system performance [20].

In conclusion, the main disadvantage of refrigerant-based is the necessity of additional components which increase the complexity of the plant layout compared to air-based and liquid-based TMSs. Furthermore, it is important to highlight that not all refrigerant-based systems can invert the thermodynamic cycle. For this reason, there are refrigerant-based TMSs which need extra electric heaters to warm up the battery during the cold season [39].

3.4. PCM-based TMSs

Phase Change Materials (PCM) are used as thermal energy storage (TES) through the solid/liquid or liquid/vapour phase transition [48]. There is a vast cluster of substances which can be used for this purpose, as kinds

of paraffin, fatty acids and hydrated salts. Their choice is based on which phase change temperature is the most appropriate for the desired applications. From cold storage to high temperature processing, the phase change temperature range can assume values in a wide and extended range defined between -50 °C to higher than 120 °C [49,50]. Adopting PCM-based TMSs can decrease the EV energy demand because, as mentioned previously, they are passive systems and do not require any electric energy to operate [39].

The main disadvantage of PCM-based systems to overcome is the low thermal conductivity: for instance, paraffin has a thermal conductivity between 0.1 W/mK to 0.3 W/mK [20]. For this reason, researchers are focusing their attention on the growth of this value by means of additional substances like graphite or metals (aluminium, copper, etc.), which can keep the same function at improved conductivity characteristics but may introduce the risk of flammability [38]. Another important issue is the occupied space: this solution is characterised by high weight and occupied volume due to the required thermal capacity of PCM masses [20].

In literature, there are examples of TMSs which use PCM to control the transient heat exchanges and stock cooling energy, but right now, these are only prototypes which are not made for mass production. For instance, Rekabra Youssef et al. [26] have developed a novel passive cooling system based on PCM for the battery pack of EVs. The proposed system uses a paraffin/graphite PCM, which is contained in plexiglass cases that surround the battery cells. In this experimental study, the maximum temperature reduction and the temperature difference

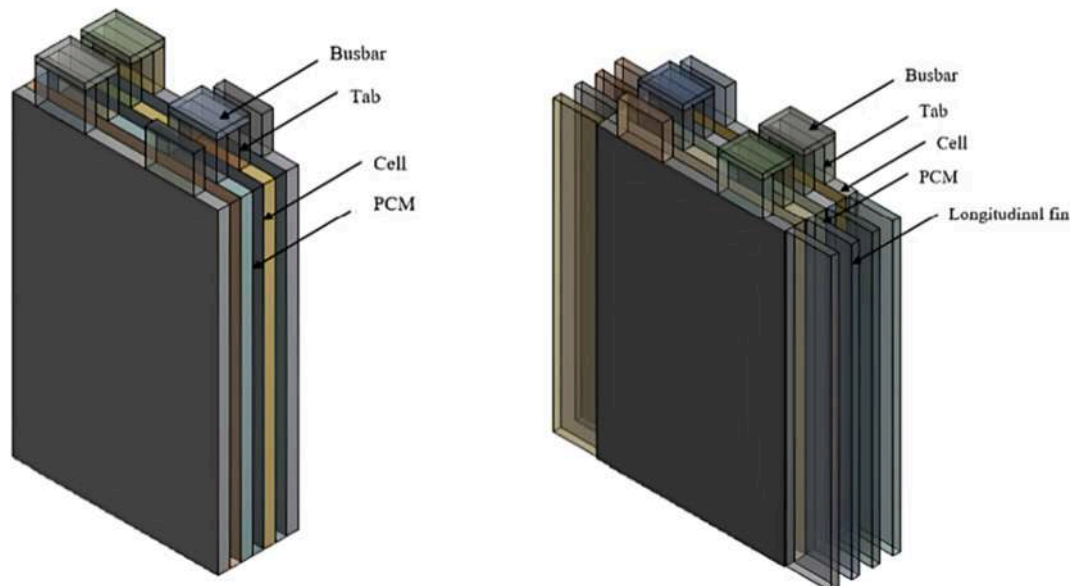


Fig. 16. PCM cooling system proposed by Ashima Verma et al. [25].

between the cells are shown in three cases: no cooling, PCM cooling and PCM plus jute fibres. The jute fibres are immersed in the PCM and, according to the authors, help the system to decrease the maximum cell temperature [26]. According to the experimental results, the PCM plus jute fibres achieved a maximum temperature reduction from 46 °C to 35 °C and good uniformity of the battery temperature field (maximum temperature difference equal to 3.1 °C). Ashima Verma et al. [25] instead proposed a new cooling system in which the PCM plates are positioned between the single battery cells. In Fig. 16 is represented the next step, which is the implementation of longitudinal fins to improve the heat exchange between the air and the cells.

One novel aspect of this research is the PCM. Generally, the material used for these systems is paraffin, but fatty acid has been considered due to its wide range of favourable properties [25]. Four Li-ion batteries have been tested and, according to the numerical simulations, the maximum temperature of the battery pack dropped by 16 °C, 22 °C and 26 °C considering three different PCM plate thicknesses (7 mm, 9 mm, and 12 mm) and longitudinal fin thick 30 mm. A good temperature field distribution was obtained with a maximum temperature difference of 5 °C.

Another interesting numerical analysis was proposed by Zhaorui Huo et al. [51] in which a novel composite material formed by paraffin and glass fibres is proposed as PCM. The main purpose of the glass fibres is to improve the mechanical structure of the battery pack and reduce the risk of thermal runaway due to the lower thermal conductivity of the glass compared to the paraffin. The numerical analysis compared a single module formed by nine Li-ion cells arranged in three parallel and three series configurations. According to Zhaorui Huo et al. [51], the best percentage of glass fibre and their orientation are 60 % and vertical to guarantee the growth of the mechanical features and the heat insulation. The numerical analysis was conducted using a thermostatic 200 °C heating rod positioned in place of the first cell during a 1C, 2C and 3C discharging state. A comparison between air, paraffin and glass fibres plus paraffin was made. In terms of heat dissipation, air, paraffin, and paraffin plus glass fibres have achieved the same results for a 3C discharging state, which indicates that the novel TMS can achieve acceptable thermal management for high discharging rates. The main advantage is related to the thermal insulation, which is fundamental to interrupting the chain reaction that triggers the fire and explosion of the battery pack [5,51]. Indeed, while the paraffin module reached a maximum temperature of 79.6 °C and a temperature difference of 35.6 °C, the glass fibres plus paraffin achieved a maximum temperature of 71.9 °C and a temperature difference of 28.3 °C. The maximum temperature of the adjacent battery through the proposed system is reduced by 10 % [51].

3.5. Heat pipes TMSs

A *Heat Pipe (HP)* is a closed-tube casing in which there is a saturated fluid that permits heat exchange through a phase change. This system is a passive TMS, and there is not any energy demand by fans or other machines because the fluid flows by means of natural convection. The working principle is based on three fundamental parts:

- *Evaporator*: this is the HP part which is in contact with the device that must be cooled. Inside this component, there is a saturated liquid which starts to evaporate and flows into the second HP part;
- *Adiabatic section*: this is the part in which the vapour flows into the third HP part. It is adiabatic, and there is no heat exchange between the fluid and the environment;
- *Condenser*: this is the part where vapour from the adiabatic section interacts with the ambient and transfers heat. The vapour condenses and becomes liquid again.

The liquid returns through the adiabatic section in the evaporator, and the process starts again. For the battery packs TMSs, three types of

heat pipes are used [27]:

- *Sintered heat pipes*: these are evacuated pipes in which a vacuum is made. There is also a porous structure called *wick*, which is placed along the whole length of the pipe. When the fluid condenses, the saturated liquid flows into the wick due to the capillary effect and returns to the evaporator;
- *Pulsating heat pipes*: these are formed by an evacuated coil filled partially with the working fluid. The pipe diameter is under the critical threshold, allowing the surface tension to be more effective than gravity. This is an important feature because it alternates liquid and vapour elements: the *liquid slugs* and *vapour plugs*. The liquid slugs evaporate in the evaporator, expand, and push the other vapour plugs into the condenser. The vapour becomes liquid and returns directly to the evaporator. This effect creates a pulsating motion which is responsible for the fluid flow through the pipe and consequently for the heat exchange;
- *Loop heat pipes*: these HPs form a closed circuit where the fluid flows from the evaporator to the condenser. The flow is made by means of the natural convection caused by the phase change.

The Heat Pipe TMSs can be used both as a battery cooling system and as a pre-heating system because the fluid flow is reversible: the evaporator can work as a condenser and vice versa due to the temperature of the batteries. Indeed, if there is a heater that can transform the saturated liquid into vapour, the fluid flows to the opposite part of the heat pipe and heats the battery pack. When the battery must be cooled down, the temperature difference between the battery pack and the ambient activates the natural convection without requesting additional external energy [39] because the operating principle is based on natural convection. Moreover, it has no moving parts, is compact, requires low maintenance and can achieve a higher thermal conductivity than other passive techniques such as the PCMs [39]. However, there are two main disadvantages: HPs have a small contact area, which means that they can operate in a small zone of the battery pack, and the thermal management of the cells is not always reached [39]. As the authors know, nowadays, heat pipes are used combined with the systems described in the previous paragraphs. For this reason, this technology will be focused on the *Hybrid TMSs* part.

3.6. Hybrid TMSs

A *hybrid TMS* combines at least two TMSs implemented to improve the system weight, volume, cost, and thermal performance [20]. In literature, there are several examples of hybrid systems, but the most used ones are a combination of liquid systems and PCM. This technique can achieve a lower energy demand because PCM can manage the transient heat exchange through the constant melting temperature and thermal inertia. However, another used combination is the heat pipes implementation in air or liquid-based TMSs. Indeed, researchers have investigated HP-assisted TMSs because this technology can improve heat dissipation efficiency due to the high thermal conductivity: it is estimated that this parameter is 90 times higher than a copper bar of the same dimensions [28].

Two examples will be reported regarding a hybrid system formed by a liquid-based system and PCMs, and another one in which the combined effect of air and liquid systems and heat pipes is studied. Huizhu Yang et al. [29] have developed a novel solution in which PCM plates have been implemented in an indirect liquid-based TMS. As explained previously, the indirect liquid-based TMSs are characterised by a cold plate in which the fluid flows through channels obtained into the slab. The proposed system permits the achievement of a lighter cooling plate by means of PCM containers positioned between the liquid channels, as shown in Fig. 17.

A total of eight hybrid cold plates containing aluminium foam composite PCM were analysed, characterised by different numbers of

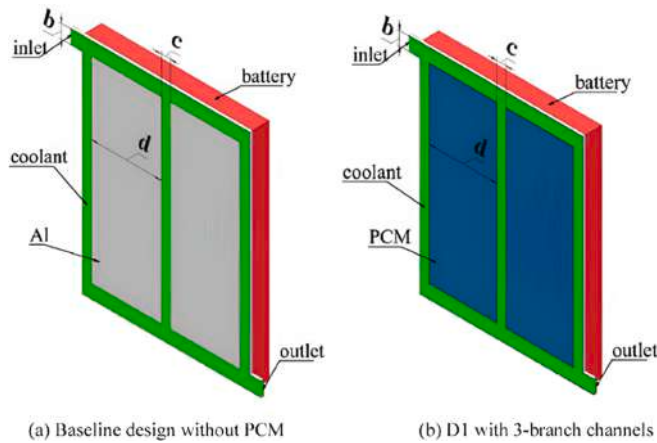


Fig. 17. (a) Reference cold plate (b) Cold plate with PCM developed by Yang et al. [29].

branches (from three to eight). In this research, a 1C discharge was considered, and the total pumping power reduction of the liquid-based system was estimated. The numerical simulations showed that the hybrid cold plate design can provide a 53 % reduction in weight compared with the baseline cooling plate design due to the lighter density of PCMs. Another important result is the pumping power, which is reduced by 90 %: according to the evaluations, this system can potentially provide more than 200 kWh savings in electric energy [29].

Hamidreza Behi et al. [28] have designed new TMSs in which the combined effect of air and liquid-based systems and HP is studied. A flat heat pipe is considered, and a preliminary study of the temperature field of the cells was made to understand which is the point of maximum temperature. Indeed, the authors explain that the optimal position for the heat pipe is the one in which the higher thermal stress is achieved [28]. Then, various TMSs are studied by means of the finite volume method to understand the temperature field changes. The first one is a natural convection air-based system which works during the discharging phase with a constant current of 184 A. It is generated at a discharge rate of 8C. The same discharge conditions are realised when the forced convection liquid-based system is considered. According to the developed model, using the hybrid system formed by the natural convection air systems and the HP, the maximum temperature is reached at the centre of the battery cells, and it is equal to 56.7 °C at the end of the discharge. Due to the high temperature reached outside the optimal range, the natural convection air-based system cannot be considered. The liquid-based TMS reaches the optimal temperature values: according to the model and experimental results, considering an inlet speed of 1 m/s, the maximum temperature reached by the battery decreases under 40 °C.

3.7. Internal self-heating

The internal self-heating is an internal heating strategy which uses the heat generated by the ohmic and polarization losses to increase the main temperature of the battery pack. This process is realised by means of the discharging phase in which a constant current or a constant voltage is generated. Part of the energy stocked in the battery is drained and converted into waste heat, which is used to increase the internal temperature of each cell. The temperature range from the minimum to maximum value can reach 40 °C of extension and warming up times lower than 10 min. In fact, according to the results reported by Xiaosong Hu et al. [8], an 18,650 cell of 2.2 Ah can be heated from a temperature of -20 °C to 20 °C within approximately 6 min using a constant voltage discharge value of 2.8 V. Due to the dependence of ohmic losses and polarization losses to the current, high discharge current intensity produces heat useful to warm up the battery cells, reducing the heating time

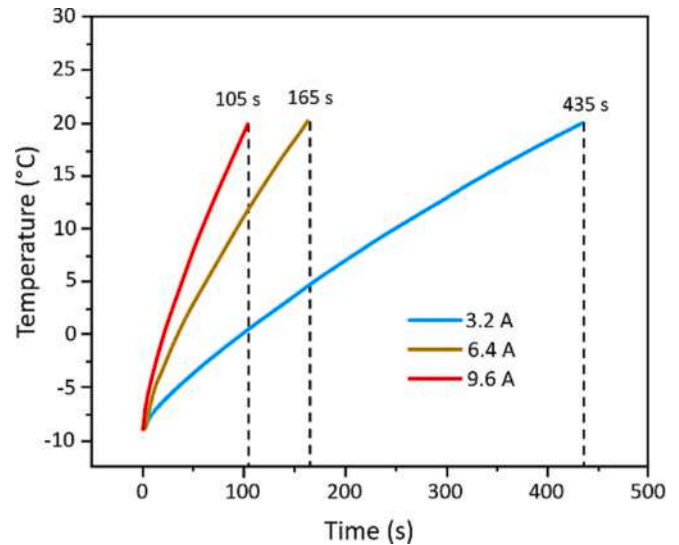


Fig. 18. Rise of the main temperature of the battery reported by Mingyun Luo et al. [34].

[8]. However, the current intensity must not be too high because, according to the cell polarization curve, it can decrease the discharging voltage near the cut-off value, which leads to an *over-discharge*. Moreover, in literature there are various experimental analyses in which the internal self-heating technique is combined with the external heating strategies described previously. One of these has been developed by Mingyun Luo et al. [34] who proposed a novel pre-heating technology in which internal heating and PCM-based TMS are considered. The system is characterised by a conductive PCM formed by a mixture of paraffin and expanded graphite. The battery pack and the PCM form a closed circuit during the discharging phase, in which both the PCM and the battery cells convert the electrical energy into thermal energy through ohmic losses. According to this study, the two electric resistances to consider are the external electric resistance related to the graphite and the internal electric resistance related to the polarization losses of each cell. Due to the contribution of the heat generated by the conductive PCM, a smaller preheating current and a faster pre-heating can be achieved [34] reducing all the issues mentioned related to a high discharging current. Fig. 18 represents the experimental results of this study, which indicate how the main temperature of the battery pack rises from -10 °C to 20 °C.

The experimental tests were conducted for three constant values of discharge current, respectively equal to 3.2 A, 6.4 A and 9.6 A, and using a battery whose capacity was equal to 3.2 Ah. The time of warming up is related to the discharge current intensity. The higher the current intensity is, the less time the heating phase takes. It is interesting to highlight that for a discharging current of 9.6 A, the time required to increase the battery pack temperature to 20 °C is less than 2 min.

3.8. Mutual pulse heating

The second internal heating strategy is mutual pulse heating. It takes advantage of the battery and other energy storages (such as capacitors or other batteries) to form an electric circuit and realise the charging/discharging process mutually [8]. Indeed, these bi-directional current pulses can generate heat inside the two mutual energy storages due to the ohmic and polarization losses to warm up the battery pack of the EV. This solution is one of the most efficient regarding the energetic analysis because, contrary to the other internal heating strategies, part of the electric energy released by the reservoir is stored in the battery cells and vice-versa. In other words, it is possible to recover part of the energy used for pre-heating because a certain portion of the output energy flow

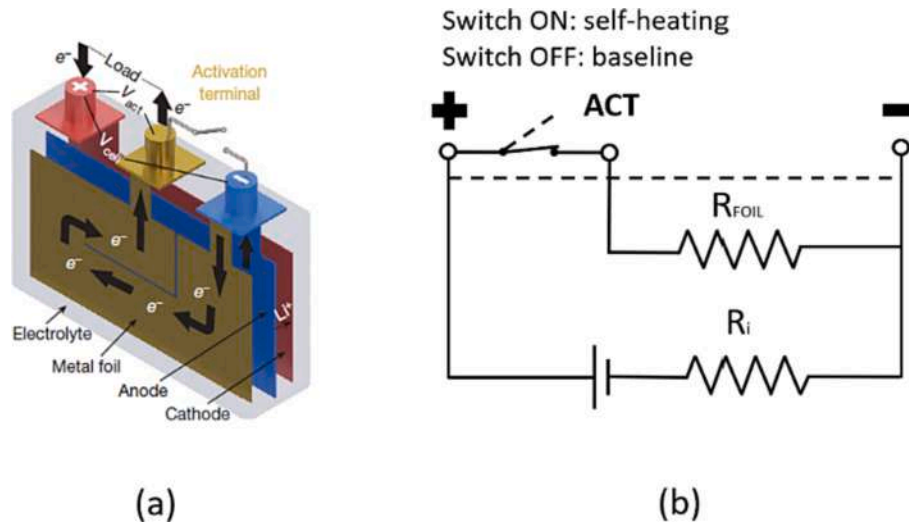


Fig. 19. (a) Architecture of a SHLB, (b) Equivalent circuit of a SHLB [36,37].

can generate heat inside the battery due to the existence the polarization and electrical losses. At the same time, the remaining amount is stored in charged cells and will be used in the next charge/discharge cycle. Indeed, according to the results reported by Xiaosong Hu et al. [8], the energy consumption of this technique could be less than 10 % of the battery capacity, reaching a temperature growth from $-20\text{ }^{\circ}\text{C}$ to $20\text{ }^{\circ}\text{C}$ in less than 220 s (about 3.7 min) when a pulsating voltage of 2.8 V is set every second. In literature, many examples of experimental analysis of this method can be found. One of these is the research conducted by Hao Zhong et al. [35] in which a novel mutual pulse heating technique is proposed for cylindrical battery cells. For this type of geometry, heat is generated in the middle of the geometry and conducted radially to the periphery during the warm-up process. From a temperature of $-20\text{ }^{\circ}\text{C}$ to $0\text{ }^{\circ}\text{C}$, the mutual heating process took 199.8 s (about 3.3 min), and the maximum value reached by the battery pack was $4.1\text{ }^{\circ}\text{C}$ with a heating rate equal to about $6.0\text{ }^{\circ}\text{C}/\text{min}$. These values are acceptable for an EV starting phase [35]. Regarding the temperature field uniformity, the maximum temperature gradient reached is equal to $4.1\text{ }^{\circ}\text{C}$ and is lower than the upper limit of $5\text{ }^{\circ}\text{C}$ [13]. The energetic consumption achieved in this experimental analysis is low because, from $-20\text{ }^{\circ}\text{C}$ to $0\text{ }^{\circ}\text{C}$, the energy consumed by the heating up system is equal to 5.99 % of the battery capacity. Furthermore, one of the goals of this experimental analysis was to demonstrate that the degradation of the battery pack capacity due to the continuous charge/discharge cycles of this technique is limited. In fact, according to the authors, after 580 repeated heating cycles, there was no obvious degradation of the battery pack cells [35].

3.9. Self-Heating Lithium-ion Battery (SHLB)

The Self-Heating Lithium-ion Battery (SHLB) consists of a novel battery structure in which thin nickel foil with a certain electrical resistance is embedded between the cells. To highlight the ability to work during all the weather, in literature this device is also called an *all-climate battery* (ACB). The functioning principle is based on a switch which connects the positive terminal to the activation terminal (ACT) connected to the nickel foil [8]. When the battery temperature is below the optimal lower limit, the switch is left closed, and an electric current is forced to flow through the battery and the metal foils, generating heat by means of the Joule effect. Once the target temperature is reached, the switch opens, the electrons bypass the nickel foils, and the normal functioning of the battery is realised. The equivalent electric circuit and the architecture of an SHLB are represented in Fig. 19.

According to the numerical analysis reported by Chao-Yang Wang et al. [36], which first proposed this novel technology, the activation

process permits fast temperature growth through favourable electrochemistry conditions inside the battery during the charging and discharging ph. In this way, the energy of the cells and the power capabilities are restored [8,36]. Indeed, their model showed that a 7.5 Ah SHBL can be heated respectively in 19.5 s and 29.6 s from $-20\text{ }^{\circ}\text{C}$ and $-30\text{ }^{\circ}\text{C}$ to a surface temperature of $0\text{ }^{\circ}\text{C}$, consuming only 3.8 % and 5.5 % of the battery capacity. Moreover, comparing the degradation between a conventional lithium-ion battery and an SHBL at a 1C discharge rate from a temperature of $-40\text{ }^{\circ}\text{C}$, the discharge power of the proposed device after the warm up was 5 to 6 times higher than a conventional one [36]. In literature, there are also other experimental analyses of this technology as the study conducted by Chao-Yang Wang et al. [37]. They realised and tested a prototype of SHBL for 14 min for increasing the main temperature from a value of $-30\text{ }^{\circ}\text{C}$ to $10\text{ }^{\circ}\text{C}$ while the cell was connected to the grid during a 3C fast charging. Generally, the charging phase in cold conditions takes about 160 min [37] while this solution can achieve 11.4 times faster charging and an improved life cycle. Implementing the charging phase through the grid was chosen to reduce a particular characteristic related to the EVs drivers: range anxiety [37]. Range anxiety is defined as a phenomenon in which the perception that a driver does not have enough energy stocked in the battery to reach the destination and is one of the fundamental parameters which is investigated when the autonomy of a vehicle is considered [52].

3.10. Alternating current heating

The last internal heating strategy is the alternating current heating. The warm up is realised utilizing an alternating current (AC) input signal, which is applied at the battery terminals to generate heat inside the device [8]. The wave shape of the current creates fast and periodical charging and discharging phases, which enable a battery pack temperature to rise from the cold environmental condition to the desired value. One of the most interesting features of this internal heating strategy is the electric energy demand: differently from the previous techniques, this solution can be achieved without extra battery energy consumption because one of the main characteristics is the connection to an external source as the grid [8,32]. In fact, AC pre-heating can be realised through the household electricity without changing the frequency and provides approximately 50 % time saving compared to low-frequency signals [32]. Unfortunately, as the authors know, there are no stand-alone applications of this internal heating strategy for EVs because most experimental tests were conducted considering an AC supplier or the connection to the electrical grid. There are future perspectives of AC preheating independent of external sources only for *Hybrid Electric*

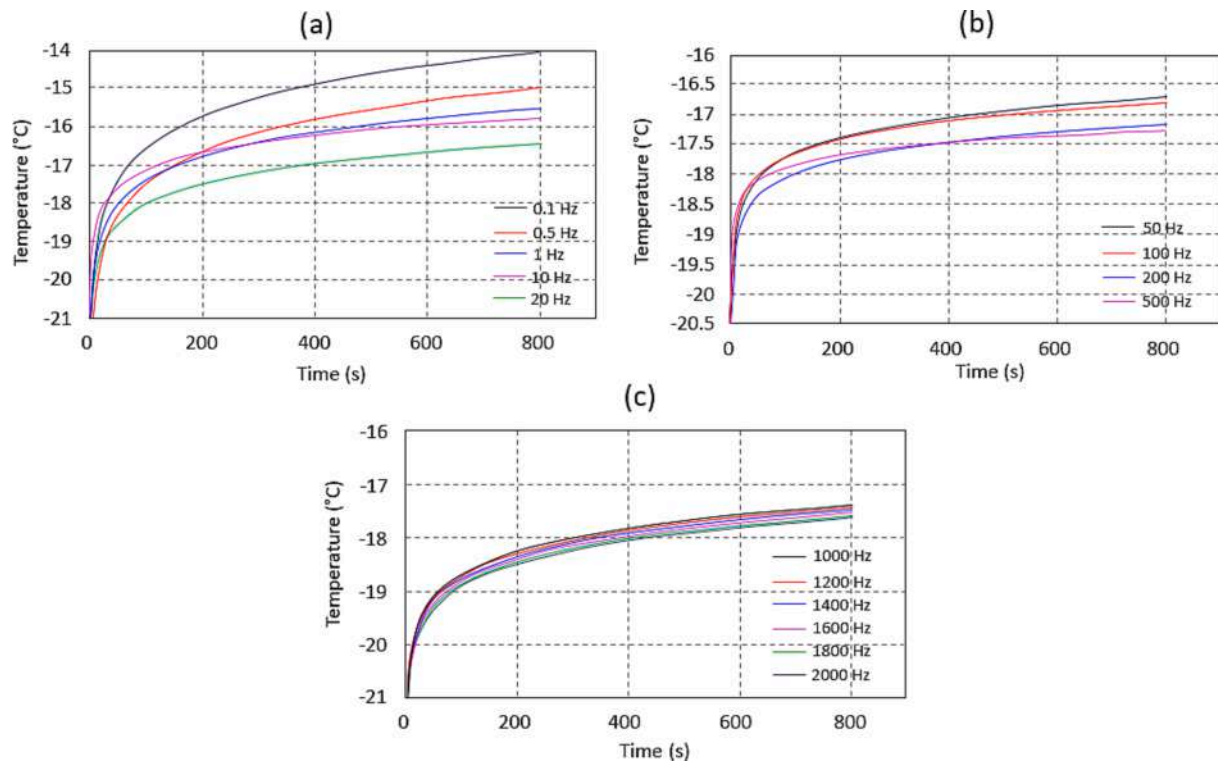


Fig. 20. Temperature growth by means of AC preheating for (a) low frequencies (b) medium frequencies (c) high frequencies [33].

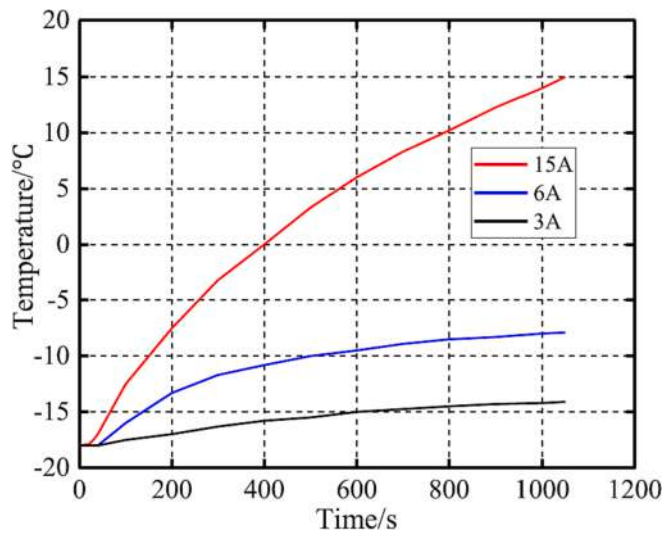


Fig. 21. Battery temperature growth under different AC amplitude [33].

Vehicles (HEVs) and Plug-in Hybrid Electric Vehicles (PHEVs) because these have Internal Combustion Engine (ICE) and alternators, which can generate the necessary AC to warm up the battery pack [32]. However, in literature there are many examples in which AC preheating is implemented to heat up Li-ion batteries of EVs. For instance, Lei Zhang et al. [33] proposed a novel multistage AC heating strategy for minimising the warm-up time without incurring the lithium plating phenomenon. An experimental analysis was made to evaluate the best frequency and amplitude of the current to find a trade-off between the life of the battery and the heating time. According to the results [33], the temperature growth curve has a similar trend for every frequency in which there is an evident rise and gradual stabilisation due to the balance between heat generation and heat dissipation towards the external

ambient. The frequency influences the speed of the warm up: the higher the frequency of the current and the lesser the time required to increase the battery pack temperature. In Fig. 20 are resumed these characteristics.

However, it is specified that the optimal frequency is equal to 100 Hz because, under this value, the battery health is affected by the lithium plating. The results showed that the current amplitude has a relevant role in AC preheating because it influences how the battery pack temperature rises during the time. This feature is shown in Fig. 21.

Three amplitudes were considered for a fixed frequency of 100 Hz: 3A, 6A, and 15A. After 1000 s, the temperature of the battery pack reached about -15°C , -10°C and 15°C for the three different values. That means the warm up time increases when the current amplitude amplifies but, at the same time, this AC characteristic cannot be too high due to the lithium plating phenomenon [33].

4. Car models and TMSs used in the automotive sector

The continuous growth of sales of EVs and the goals established by the European Union in 2035 encouraged the main car manufacturers to develop new models and solutions to spread the use of this technology around the world. For example, these are accomplished car brands such as Audi, BMW, Mercedes-Benz, Nissan, and Toyota and sports brands such as Porsche and McLaren. This paragraph highlights the thermal management systems of the available or soon available EVs in the mass production market, describing the strategies chosen for the cooling down and the warming up of the battery pack. The models reported afterwards are chosen according to the satisfying quantity of information reachable on the official sites of manufacturers or specialised magazines of automotive. This is the order in which they will be presented:

- *Sports cars*: Audi e-tron GT quattro [53,54], McLaren Speedtail [55,56] and Porsche Taycan [57];
- *Sedan cars*: BMW i4 eDrive 40 [54,58] and Mercedes EQS [54,59–61];

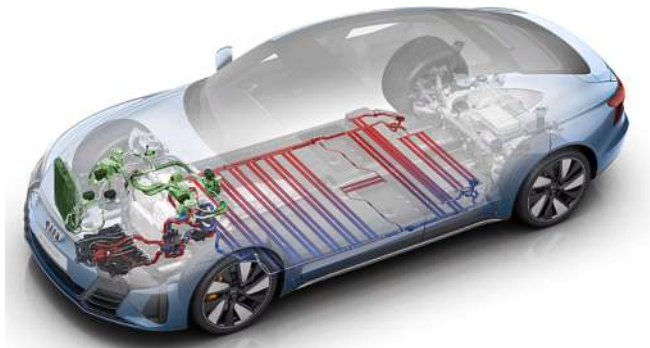


Fig. 22. Audi e-tron GT quattro liquid-based TMS [53].

- Crossover: Tesla Model Y [62–64];
- SUV: Nissan Ariya [54,65–67], Toyota BZ4X [54,68] and Volkswagen ID.4 [54,69,70].

The Audi e-tron GT quattro is a sports EV released by Audi in 2021 [54]. As reported by the official site Audi MediaCenter [53] and the site Electric Vehicle Database [54], this sports car has a Li-ion battery system which is characterised by a nominal power of 390 kW and is formed by 396 cells which can store 84 kWh of energy net (93 kWh gross). The battery system is located beneath the passenger compartment because one of the main goals is to maintain a low centre of gravity and achieve more stability. According to the information reported by Audi, the TMS used for this model is an indirect liquid-based system formed by a cooling plate which separates the cells and the working fluid. The substance used is a water and glycol mixture, and it is cooled down or warmed up by the HVAC system, which works as a refrigerator machine during the hot season and a heat pump during the cold climates. The main information given by the manufacturer is the temperature range of the battery: the TMS can maintain the battery pack temperature between 30 °C and 35 °C. Moreover, Audi declares that the system can manage the main temperature of the battery pack for ambient conditions between –30 °C to 50 °C. In Fig. 22 the Audi e-tron GT quattro and its TMS is represented.

The second sports car object of analysis is the McLaren Speedtail, which is a hybrid electric vehicle. Indeed, the M840TQ powertrain is formed by a 4.0 L internal combustion engine combined with an electric drive unit which can achieve a total power of about 790 kW, which is 230 kW derived by the electric motor [55]. Moreover, the 270 kW Li-ion battery pack is formed by high-power cylindrical cells, which are arranged in a unique array and can store 1647 kWh gross of energy. This value is confirmed by the great power density of the battery pack, equal to 5.2 kW/kg [55,56]. The innovation brought by this sports car is achieved, especially by the TMS, because the McLaren Speedtail is the first car available on the market to implement the immersed liquid-based technique. The battery cells are permanently immersed in a lightweight dielectric oil to improve the heat exchange, allowing them to deliver greater performance for longer [55,56].

The third sports car presented is the Porsche Taycan. Porsche has developed the Performance Battery Plus, which is located underbody of the car, achieving a low centre of gravity, thus the sporty driving style [57]. This battery pack is formed by a sandwich construction, which is divided into multiple subdivisions as the waterproof housing and the battery housing. The battery frame is made of lightweight aluminium, which provides a lot of installation space for the cells and increases the battery capacity [57]. These characteristics permitted the manufacturer to insert 33 modules of 12 individual cells each, which can store a gross amount of energy equal to 93,4 kWh. The TMS is an indirect liquid-based system integrated into the vehicle cooling circuit via a line system and a coolant pump [57]. The inverse machine works as a

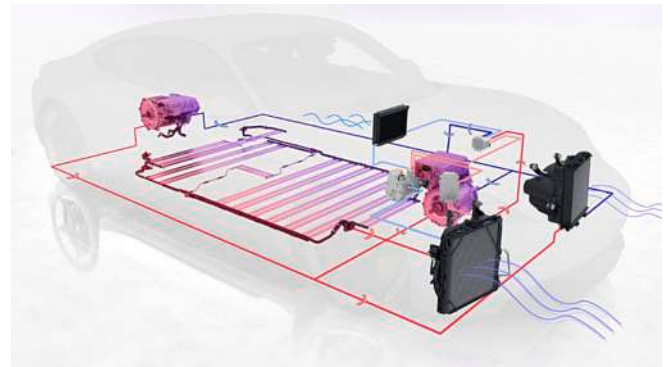


Fig. 23. Porsche Taycan indirect liquid-based TMS [57].



Fig. 24. BMW i4 eDrive40 liquid-based TMS [58].

refrigeration unit during hot climates and can be used as a heat pump during the cold season for warming up the battery pack. In Fig. 23, the TMS of the Porsche Taycan is represented.

Another interesting feature is the role of the battery as storage of wasted heat from the liquid-cooled high voltage components. Indeed, the warm-up of the battery is realised by means of the wasted thermal energy from other components of the powertrain, which can ensure recovery of heat useful to increase the temperature of the cells when necessary [57].

In the sedan cars group, one of the models available on the market is the BMW i4 eDrive40. This EV has a Li-ion battery pack formed by four 72-cell modules and three 12-cell modules (324 cells in total), which can stock 84 kWh, whose 81 kWh are effectively usable [54,58]. According to Ampacity [58], the powertrain electric motor is an ESM (excited synchronous motor) with an overall efficiency of 93 % and can provide up to 250 kW between 8000 rpm and 17000 rpm. Regarding the battery pack TMS, as in the previous models, the BMW i4 eDrive40 has an indirect liquid-based TMS for the battery pack characterised by control valves and units for the HVAC system, which can heat up or cool down the cells using any combination of the three circuits and one expansion tank. Moreover, the TMS can recover heat from the engine and the power electronics to increase the main temperature of the battery and the internal cabin in cold weather, reducing the energy demand of the system [58]. In Fig. 24 the BMW i4 eDrive40 liquid-based TMS is shown.

In recent years, Mercedes-Benz proposed a new series of EVs called Mercedes EQ. In particular, the sedan car of this group considered for this review is the Mercedes EQS which is available in two different powertrain architectures: Mercedes EQS 450 + and Mercedes EQS 580 4MATIC. A rear-wheel drive system characterises the Mercedes EQS 450 + with a single motor that can produce a nominal power of 245 kW [54,60]. Instead, the EQS 580 4MATIC is an all-wheel drive car whose powertrain can supply a nominal power of 385 kW distributed among the rear and the front axles, respectively 255 kW and 135 kW [60]. For both models,

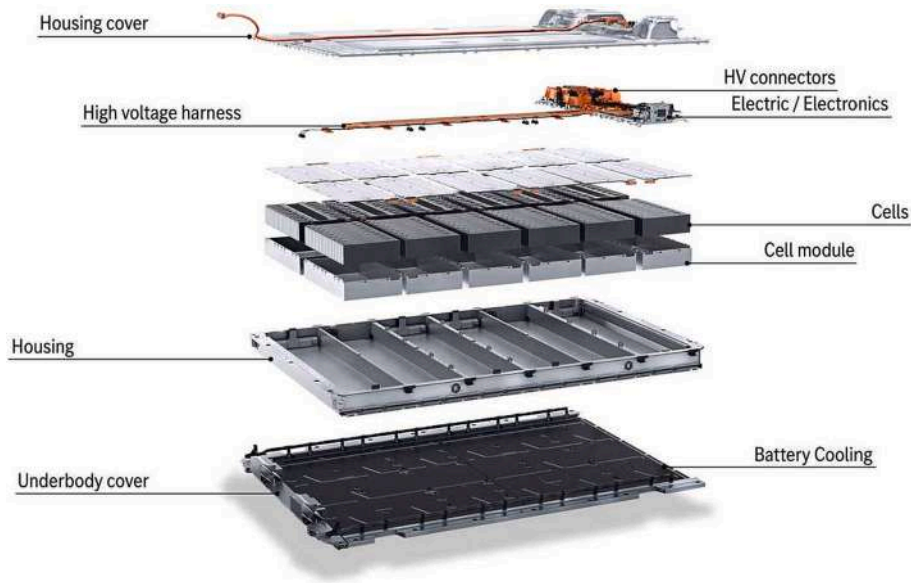


Fig. 25. Mercedes-Benz EQS battery pack and cooling plate [59,60].

the regenerative braking can recover a maximum power of 290 kW by means of the permanently excited synchronous electric motors [59,60]. The storage capacity of the Mercedes EQS depends on the number of cells chosen for the battery pack, which 10 or 12 modules can form. Considering a capability of 9 kWh for each module, the total capacity of

the Li-ion battery is equal to 90 kWh or 107.8 kWh [60]. The battery pack temperature is managed by an indirect liquid-based TMS, which uses a bottom cooling plate in which the coolant flows in cavities obtained on its surface. This solution is shown in Fig. 25, in which also the main other parts of the battery pack are represented.

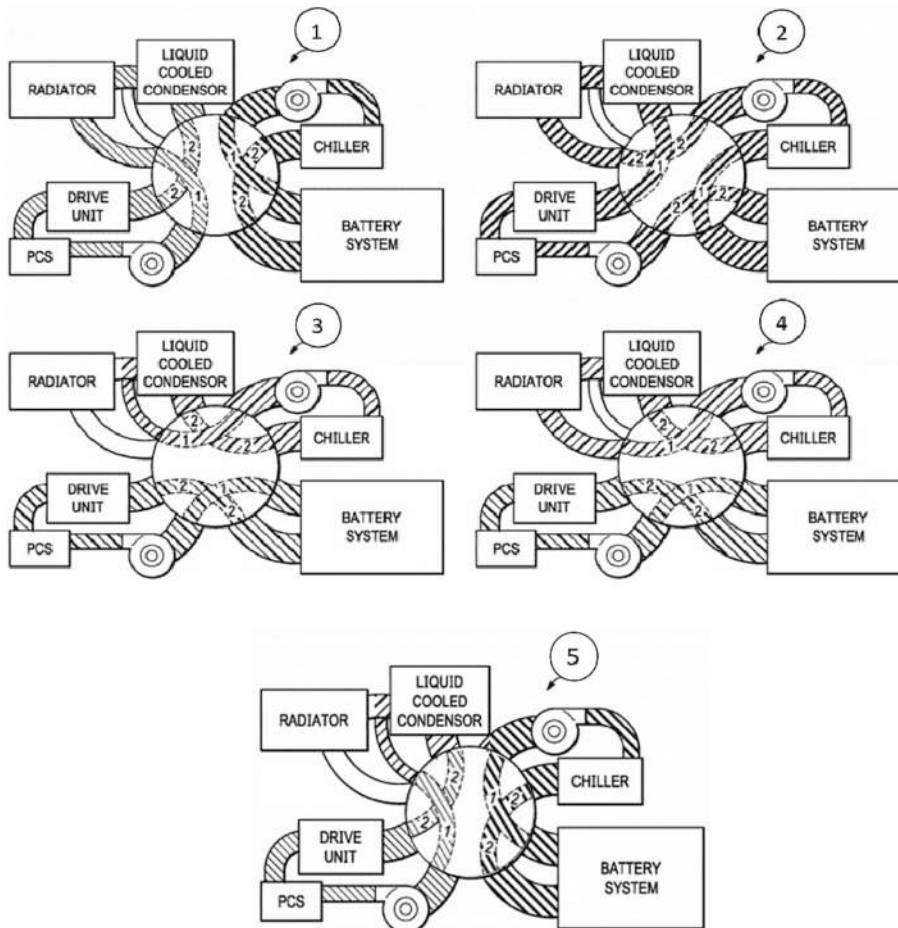


Fig. 26. Octovalve states reported in the Tesla patent [64].

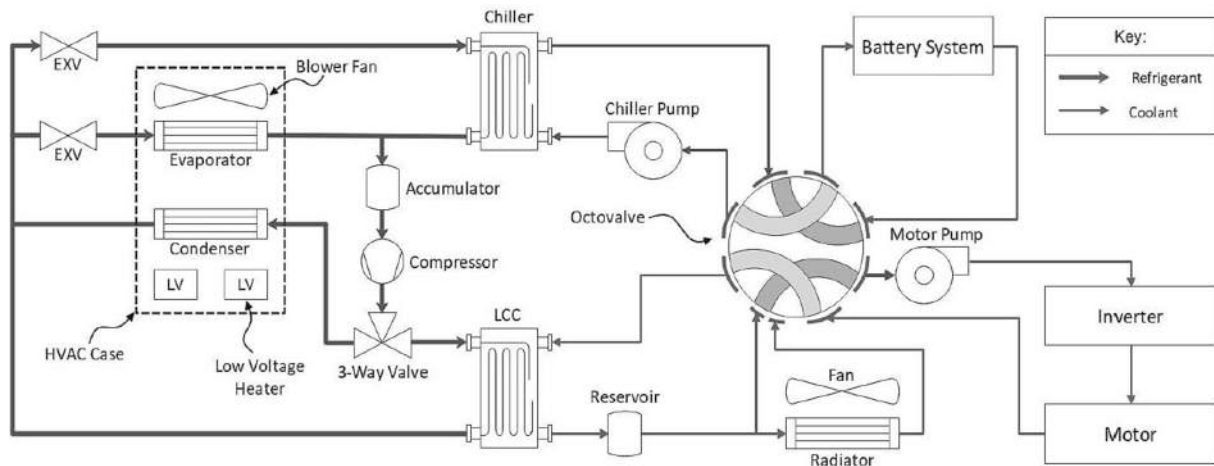


Fig. 27. Complete scheme of the Tesla Model Y TMS [63].

The TMS can control the temperature of the Li-ion cells while driving or during the charging phase by means of an Electric Intelligence, which can reduce the charging times and maintain the main temperature in the optimal range [60,61]. Moreover, this system uses a *Positive Temperature Coefficient (PTC) Heater*, which is an electric heater that the TMS must use when the ambient temperature reaches values in which the heat pump loses performance [71]. Indeed, an electric heater offers a simple structure and a fast response due to the PTC element, which permits a self-regulation function. This part of the device can change its resistance due to environmental temperature changes regulating the heat required to control the battery pack thermally.

Tesla Model Y is the new crossover developed by the American EVs manufacturer Tesla, available since November 2022. As reported by Electric Vehicle Database [54], this electric car has a Lithium-ion battery with a gross capacity equal to 60.0 kWh, whose effectively usable is 57.5 kWh. The battery pack is characterised by a maximum power of 220 kW produced by 106 Lithium cells, which supply a dual motor system. In fact, according to the official site of Tesla [62], all-wheel drive is the technique used for the Model Y in which two independent electric motors digitally control torque to the front and the rear wheels for far better handling, traction, and stability control. Regarding the powertrain TMS, as other vehicles analysed previously, Tesla implemented an indirect liquid-based system in which the HVAC system of the car controls the temperature of the coolant. Alex Wray et al. [63] have analysed the Model Y TMS, describing the most innovative features and how it works for the different requests of the powertrain and cabin conditioning. The main attention of this novel technology is concentrated on a new component patented by Tesla in 2019 [64] called *octovalve* which is represented in Fig. 26.

As shown in the picture, the octovalve is a rotation valve which has eight ports and allows the coolant to flow in five unique states, each one capable of multiple functions depending on the system operation. In particular:

- The valve in state 1 shows one loop dedicated to the driver unit (inverter and motor) and the radiator, while the second loop is dedicated only to the battery. In particular, the interaction with the inverse machine is realised by means of a Liquid Cooled Condenser (LCC) for the first loop, while the second one is realised by means of a chiller;
- The valve in state 2 permits the flow of the coolant in each component in one unique loop in which the devices are put in series;
- The valve in state 3 permits the flow of the coolant in two different loops in which the LCC and the chiller are connected in the first one while the battery system and the drive unit are linked together in the second one. The radiator is by-passed by a secondary pipe;

- The valve in state 4 permits the same functions as state 3, but the radiator is not by-passed and receives coolant by the pump connected to the chiller and the LCC;
- The valve in state 5 permits the same functions as state 1, but the radiator is bypassed.

Once the octovalve operating functioning is shown, it is necessary to understand how this device is implemented in the circuit. The complete scheme of the TMS is shown in Fig. 27.

The inverse machine is formed by a single electrical compressor, a 3-way valve, the LCC and the chiller, the cabin condenser and evaporator, and an accumulator. It can operate as a refrigeration machine in hot weather and as a heat pump in cold climates. The main characteristic is using two parallel condensers (the cabin air condenser and the LCC) and two parallel evaporators (the cabin air evaporator and the chiller), which permits independent control of the cabin conditions and the powertrain thermal management. Moreover, the scheme in Fig. 27 have no external condenser, and for this reason, the cabin condenser or the radiator must be used to transfer heat to the ambient [63]. This novel plant proposed by Tesla permits the Model Y to achieve 12 different heating modes and three different cooling modes. According to the data reported by Alex Wray et al. [63], the system can pre-heat the battery pack for ambient temperature lower than $-10\text{ }^{\circ}\text{C}$ and can maintain the main temperature of the cells between $30\text{ }^{\circ}\text{C}$ and $35\text{ }^{\circ}\text{C}$ during hot climates.

Nowadays, also in the SUV sector, car manufacturers have proposed new EV models available or soon available in the market. The first one reported in this paper is the *Nissan Ariya*, which is an electric car available on the market since 2022 [54] and the successor of the *Nissan Leaf* [67]. Nissan launched two different configurations whose difference is based on the battery pack capacity and nominal power: the B6 version and the B9 version. The first has a battery pack whose gross capacity and power are respectively equal to 66.0 kWh and 160 kW, while the second has a more capacious energy storage of 87.0 kWh and is characterised by an electric power of 178 kW [54]. Regarding the battery pack TMS, Nissan changed its philosophy by introducing an indirect liquid-based TMS instead of the air-based system used on the *Nissan Leaf* [65]. In particular, the cooling down is realised utilizing a chiller, which decreases the liquid temperature, while the heating up in cold weather is made through a heater in parallel with the battery pack. In Fig. 28, the coolant loop of this TMS is represented.

The Long Life Coolant (LCC) [66] exchanges heat by means of a cooling plate in which it flows through separate channels. Furthermore, the liquid must be supplied uniformly across the entire slab but with a reduced thickness to reduce the bulk and the weight of the battery pack. For this reason, the heat exchanger comprises three layers: the lower

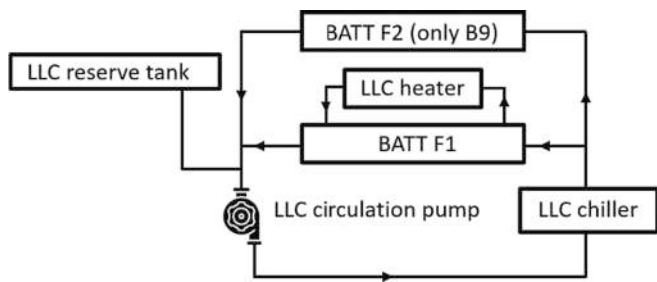


Fig. 28. Nissan Ariya liquid loop of the TMS [66].

plate, LLC flow channels and protection cover. The lower plate is characterised by a cross-section in which the LLC flows under the modules. The cavity in which the pipes are positioned is hollow to direct the heat flow to the battery and decrease the dispersions [66]. This structure is represented in Fig. 29.

The *Toyota bZ4X* is the novel electric SUV available since June 2022 [54]. As reported by the official site Toyota Europe Newsroom [68], this model is the first all-new EV of Toyota, and its name derives from the sub-brand “Beyond Zero”, whose scope is to start a new era of production of fully electric cars. Moreover, this SUV was designed and

projected in collaboration with Subaru, which gave the know-how in various areas such as all-wheel drive engineering. The *bZ4X* is available in front and all-wheel drive versions: the *Toyota bZ4X FWD* and the *Toyota bZ4X AWD*. They have the same battery pack formed by 96 cells, which can stock a gross amount of energy equal to 71.4 kWh (usable 64.0 kWh) while the nominal power supplied by the powertrain is respectively 150 kW and 160 kW [54,68]. In particular, the AWD model, as the all-wheel drive cars shown previously, has two different electric motors for each axle in which the total power of the vehicle is distributed equally (80 kW for each axle) [68]. Regarding the TMS, also in this case, the technology adopted is the indirect liquid-based technique, which enables the *Toyota bZ4X* to work in an ambient temperature range between $-30\text{ }^{\circ}\text{C}$ and $60\text{ }^{\circ}\text{C}$. Furthermore, as reported by the official site of Toyota [68], this is the first Toyota electric car to adopt a water TMS, which is paired with the HVAC that works as a heat pump during the cold season and as a refrigerator machine during the hot weather to warm up and cool down the liquid coolant. Another interesting feature is the optional solar panel roof available in selected markets [68]. The solar panel charges the main battery, ensuring a sufficient distance to empty and allowing power to be supplied for other purposes (such as electrical appliances).

The last SUV analysed in this paragraph is the *Volkswagen ID.4*. This vehicle is part of a new EV range launched by Volkswagen in 2020 called

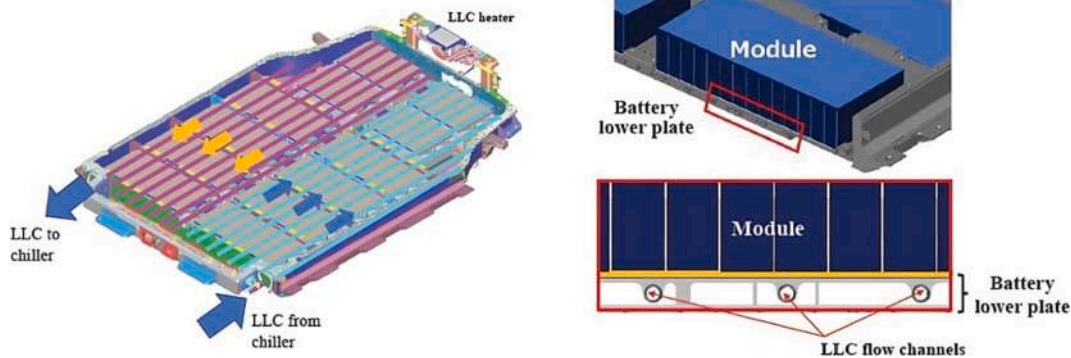
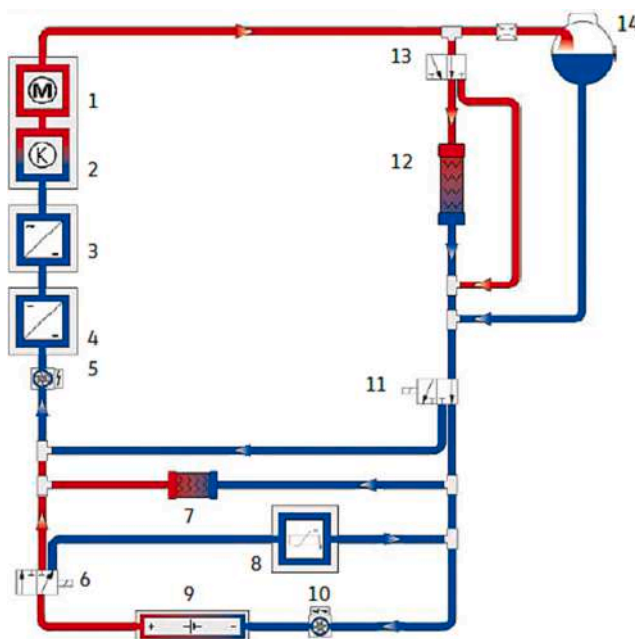


Fig. 29. (a) Nissan Ariya heat exchanger structure and detail of the LLC pipes [66].



1. VX54 Three-Phase Current Drive
2. JX1 Electric Drive Power and Control Electronics
3. AX4 High-Voltage Battery Charger 1
4. A19 Voltage Converter
5. V468 Low Temperature Circuit Coolant Pump
6. V683 Mixing Valve for High-Voltage Battery Warming
7. Heat Exchanger for Heat Condenser
8. Z132 Heating Element (PTC) 3
9. AX2 High-Voltage Battery 1
10. V590 High-Voltage Battery Coolant Pump
11. V696 Mixing Valve 2 for High-Voltage Battery Warming
12. Radiator
13. Thermostat
14. Coolant Expansion Tank

Fig. 30. Volkswagen ID.4 TMS layout [70].

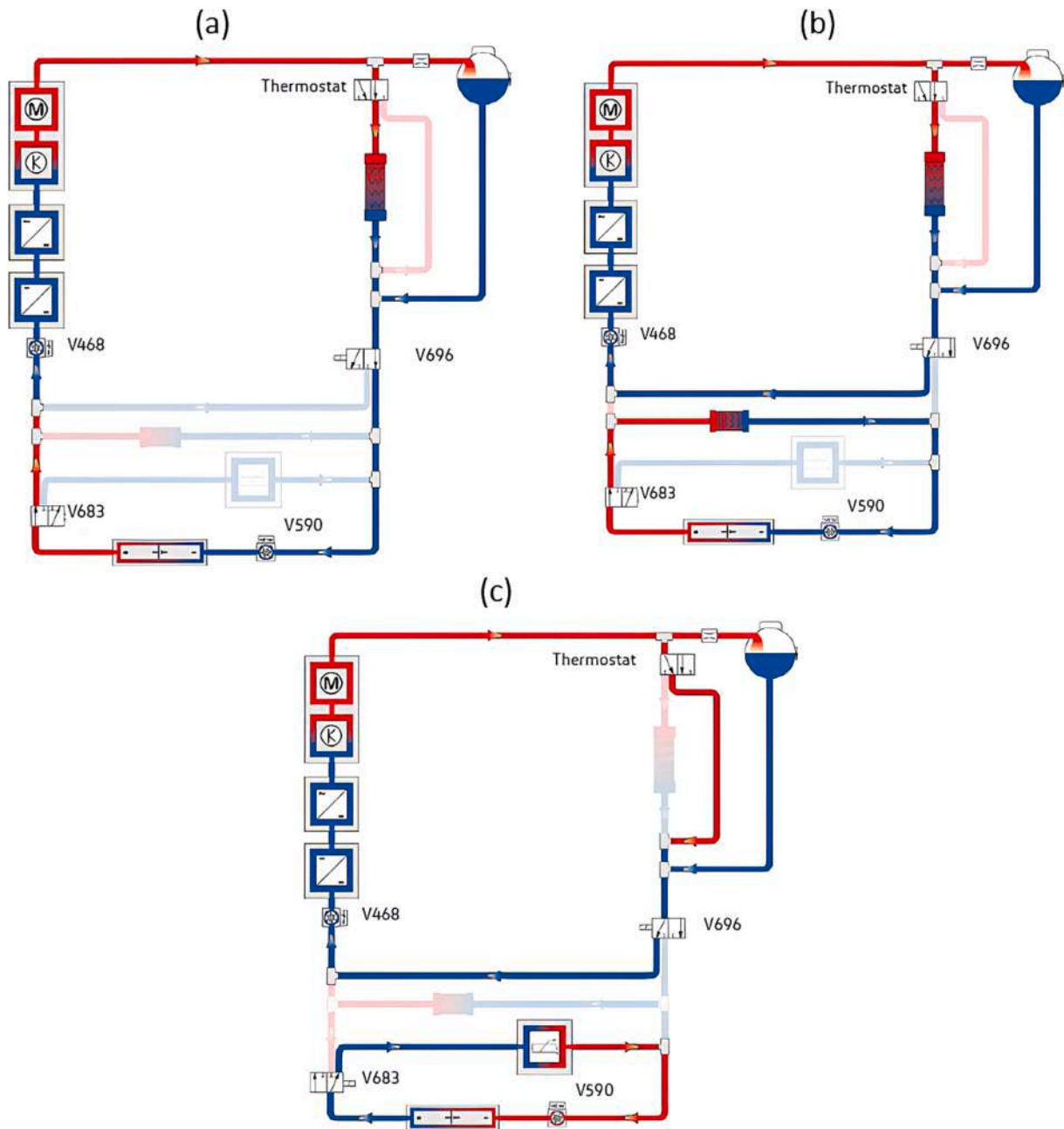


Fig. 31. Liquid loop for (a) cooling phase by means of the radiator, (b) cooling phase by means of HVAC, (c) heating phase by means of the PTC heater [70].

Volkswagen ID [69] which is completely comparable to what Mercedes-Benz and Toyota did for the EQ and bZ series. The Volkswagen ID.4 is available in different configurations in which the powertrain power and the Li-ion battery capacity change [54]. The first one is the *Volkswagen ID.4 Pure*, which can supply a power of 109 kW and a nominal capacity of 55.0 kWh, whose 52.0 kWh are effectively usable. A rear-wheel drive characterises the model, and the battery pack comprises 192 cells. Instead, the *Volkswagen ID.4 Pro* has a rear-wheel drive powertrain that can release a total power of 150 kW and store a nominal amount of energy equal to 82.0 kWh, whose effectively usable is 77.0 kWh. For both configurations, the thermal management of the battery pack is realised by an indirect liquid-based system, which permits the vehicle to operate between ambient temperatures of $-28\text{ }^{\circ}\text{C}$ and $60\text{ }^{\circ}\text{C}$ [70]. In Fig. 30, the liquid circuit of the Volkswagen ID.4 TMS is represented.

The heating up is managed through the HVAC system condenser (7) and the PTC heater (8), while the cooling down can be realised by means

of the HVAC system or the radiator (12) [70]. Three different switch variants of the liquid loop are illustrated in Fig. 31.

As reported by Volkswagen [70], loop (a) allows the temperature battery pack to decrease through liquid coolant, which is cooled down by the external radiator without any request from the HVAC system. This configuration activates when the battery pack temperature reaches values over $30\text{ }^{\circ}\text{C}$ and the thermostat measures an ambient temperature over $15\text{ }^{\circ}\text{C}$. Instead, loop (b) cools down the battery cells by means of the air conditioning system in refrigerator machine mode. This strategy is chosen when the thermostat measures a temperature under $15\text{ }^{\circ}\text{C}$ and the battery pack reaches a temperature over $35\text{ }^{\circ}\text{C}$ during the vehicle operation. Furthermore, this system activates also when the EV is in charging mode and the temperature of the cells is over $30\text{ }^{\circ}\text{C}$. The loop (c) is used when it is necessary to increase the battery pack temperature. This condition is realised when the temperature of the Li-ion cells is under $8\text{ }^{\circ}\text{C}$, and the thermostat samples an ambient temperature under

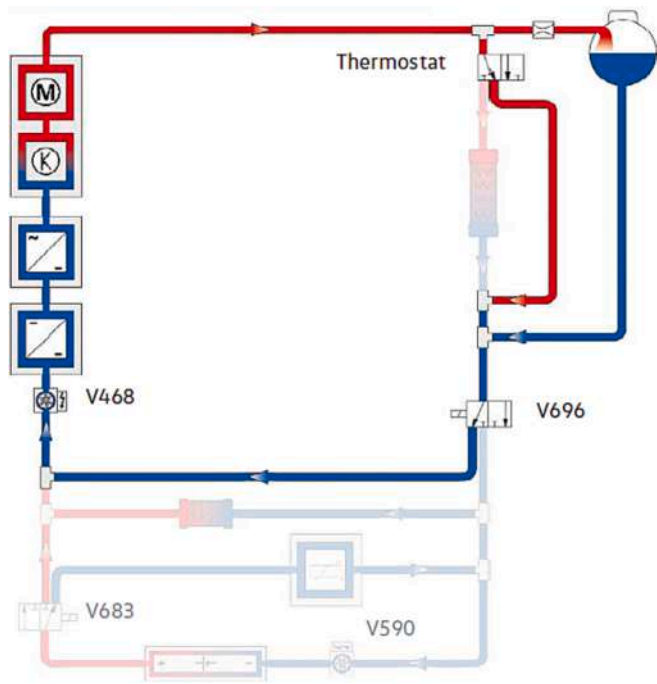


Fig. 32. Volkswagen ID.4 liquid loop and battery by-passed [70].

15 °C. In addition, as shown in Fig. 32, there is another condition in which the battery is not cooled or heated, and it is by-passed.

This loop is used when the heat exchange between the cells and the environment satisfies the heat dissipation of the battery pack. This happens when the thermostat measures an ambient temperature under 15 °C, and the battery temperature reaches values between 8 °C and 35 °C.

5. Current status, challenges and future direction of technology

In the previous paragraphs, several TMSs developed in the last years and new proposed technologies regarding the heating-up strategies have been shown. Moreover, the principal solutions brought by car manufacturers have been reported to fully understand which path the market follows to create new efficient EVs. Currently, the most mature technologies are air-based and indirect liquid-based TMSs, demonstrated by various EVs that were and are available on the market. Indeed, multiple EVs launched in the first years of 2000 and now out of production have been characterized by air-based TMSs such as the *Honda Insight* [72] and the *Nissan Leaf* [73]. Gradually, air-based TMSs have been substituted by liquid-based systems. For instance, as mentioned before, Nissan changed its philosophy by introducing the *Nissan Ariya*, whose TMS is based on an indirect liquid coolant technology [67]. In general, as shown in Table 2, most of the EVs launched recently by car manufacturers use an indirect liquid-based TMS due to the higher efficiency than air-based

TMS, thanks to the higher convective heat transfer coefficient between the coolant and the battery cells.

Even though there are different well-known TMSs in the EVs field, the research must focus on several challenging issues. These are both related to the cooling-down and the warming-up phases. The first one is the phenomenon of thermal runaway, which is the primary cause of fire and explosions of the powertrain due to high temperatures or mechanical abuse of the battery pack. The second one is the heat generation during the discharging and charging mode, in which, due to the polarization losses, part of the chemical energy stored in the battery is converted into wasted thermal energy that increases the temperature of the cells. The TMSs must be able to maintain the temperature field of the powertrain in the optimal range in every environmental condition, reducing to the minimum the energy demand and preserving vehicle autonomy. In cold weather, the most challenging requirement of an EV is starting in every condition, especially when the ambient temperature is very low (below -20 °C) [8]. For this reason, the TMS must be able to heat the battery cells to withdraw electric energy (essential to power up the electric motor) and reduce the typical lack of efficiency of the Li-ion batteries at low temperatures. Although many car manufacturers declare their vehicles can work in challenging environmental temperatures (such as -10 °C and -30 °C as reported in Table 2), one fundamental aspect to consider is the heating ratio. The external heating strategies have not yet reached a satisfying warming-up time, and the procedure can take several minutes. Indeed, considering air-based and liquid-based TMSs, the system takes about 20 min to increase the average temperature of the battery pack from a value between -15 °C and -10 °C to 0 °C [8].

To overcome these issues, researchers and automotive manufacturers are developing new TMSs which define a new future direction for the cooling and warming of the battery packs of EVs. According to the forecast [74], active cooling and warming technology (air-based, liquid-based) will remain similar and dominant in the automotive market. The liquid-based systems will continue to use a large cold plate beneath or above the cells, but the major innovation will be regarding the interface material between the cells and the cold plate and the introduction of novel liquid fluids. Thermally conductive adhesives will be used to make a structural connection to fill typical gaps formed between the battery pack and the metallic plate which are filled with air and are thermal insulating. Furthermore, to increase the thermal conductivity of the coolant, new substances with better thermal properties than the classical mixture of water and glycol will be adopted. Indeed, new liquid fluids will be implemented as:

- *Dielectric oil*: dielectric oil is used as a coolant for immersion liquid-based TMSs, but due to the high viscosity, its heat transfer efficiency is only 1.5—3 times higher than that of the air-based TMS at the same pumping power [75]. Moreover, its physical properties cause fluid leakage [75] which is one of the reasons why the immersive liquid technique is not as common as the indirect one yet;
- *Nanofluids*: nanofluids are liquids in which there are incorporated solid particles generally made in aluminium, copper, nickel, silver, or

Table 2
Summary of new EVs launched on the market and their TMSs.

Model	Type of Car	Gross Battery Capacity	Powertrain Power	Cooling and Heating Technology	Declared Ambient Temperature Working Range
Audi e-tron GT quattro	Sports car	93 kWh	390 kW	Indirect Liquid	From -30 °C to 50 °C
McLaren Speedtail	Sports car	1647 kWh	790 kW	Immersive Liquid	Not available
Porsche Taycan	Sports car	93.4 kWh	350 kW	Indirect Liquid	Not available
BMW i4 eDrive 40	Sedan car	84 kWh	250 kW	Indirect Liquid	Not available
Mercedes EQS	Sedan car	90 kWh – 107.8 kWh	245 kW – 385 kW	Indirect Liquid	Not available
Tesla Model Y	Crossover	60 kWh	220 kW	Indirect Liquid	Not available
Nissan Leaf	SUV	66 kWh – 87 kWh	160 kW – 178 kW	Indirect Liquid	Not available
Toyota bZ4X	SUV	71.4 kWh	150 kW – 160 kW	Indirect Liquid	From -30 °C to 60 °C
Volkswagen ID.4	SUV	55 kWh – 82 kWh	109 kW – 150 kW	Indirect Liquid	From -28 °C to 60 °C

metal oxides (such as Al_2O_3 , CuO , Fe_3O_4 or TiO_2) or silicon dioxide (SiO_2) to increase the thermal conductivity [75–77]. For instance, according to Liu et al. [78], adding copper particles in a conventional fluid in a concentration of 0.1 vol% can increase the thermal conductivity by 23.8 %;

- *Liquid metals*: various liquid metals, like mercury or gallium, can be used as new coolants due to higher thermal conductivity than water and lower viscosity than oil. These fluids flow in pipes through an electromagnetic pump, which is quieter and less vulnerable than conventional pumps [75].

Regarding how fluids interact with the battery pack, dielectric oils open new perspectives to the immersion liquid technique. The example of the McLaren Speedtail may be a pioneering application of this technique for other types of vehicles different from sports cars. Otherwise, in the last years, there were examples of cars implementing a refrigerant-based TMS. For instance, the *BMW i3*, launched in 2017, used the HVAC refrigerant to manage the temperature of the battery pack during the hot and cold seasons [79]. It is not excluded that car manufacturers will develop EVs characterized by this type of TMS due to the excellent efficiency of a two-phase heat exchange between the Li-ion battery cells and the fluid.

Regarding future developments and perspectives of research, a novel concept of thermal management of battery packs is presented by static devices such as *Thermoelectric Modules (TEMs)*. TEMs are lightweight, noiseless, and compact active thermal components able to convert electricity into thermal energy through the Peltier effect. These devices will continue to receive much attention due to several advantages, such as compact size, no moving parts and working fluid, and easy switch between cooling and heating modes [80]. The results obtained through recent investigations indicate the TEMs will achieve good results comparable to the classical TMSs mentioned previously. For instance, Zhaozang Yi et al. [81] proposed a novel technology based on a high-efficiency double-sided thermoelectric device whose cooling and heating modes can be switched by changing the current direction. According to the experimental results, the maximum temperature of a 5 W battery maintains a constant value equal to 25 °C and a maximum temperature equal to 4.7 °C to maintain the average temperature in the optimal range.

6. Conclusions

Thermal Management Systems are a fundamental part of the electric vehicle powertrains and are indispensable to control the average temperature of the battery pack. In this review, the main purpose of the authors was to compare, from a thermal engineering point of view, the literature studies and the recent technical solutions launched on the market. This analysis may be helpful to understand how the automotive industry recaps the innovations brought by academics and to highlight which is the connection between research and manufacturers.

In literature, there are several methods and techniques to manage the temperature of battery packs in hot and cold seasons using active systems (as air-based, liquid-based, and refrigerant-based techniques) or passive systems such as PCMs and HPs. A new perspective is given by internal heating strategies which can reach higher heating rates than conventional warming up systems. Still, this technology is not mature yet for a possible introduction to the market due to the formation of lithium plating and the shortage of stand-alone applications. Several numerical and experimental papers have been reported to fully understand which path is followed to increase the efficiency of TMSs. The main intention of these studies is to achieve an improved heat exchange by employing new shapes of ducts and cold plates, new plant schemes to increase efficiency. The introduction of passive techniques, as PCMs, permits a reduction of the energy consumption of the TMS because the thermal inertia of substances in phase changing can maintain a constant temperature during the time without requiring any energy demand.

Moreover, the low thermal conductivity of PCMs is a characteristic helpful to overcome the thermal runaway phenomenon because the Li-ion cells are each other insulated.

Successively, nine models of EVs (sports cars, sedans, a crossover and SUVs) have been reported to understand how prestigious brands are approaching the thermal management matter. Searching on the official sites and specialised magazines of automotive, most of the new vehicles launched on the market use indirect liquid-based TMS whose temperature is managed by the HVAC system of the car. Several manufacturers, as Nissan and Honda, changed their philosophy, abandoning the air-based technique in favour of the liquid-based TMSs due to their higher efficiency of the convective heat exchange. BMW followed a similar approach by substituting the refrigerant-based concept implemented in the *BMW i3* to the liquid-based technique used on the *BMW i4 eDrive 40* and in agreement with the competitors. Regarding the thermal management of battery packs during hot and cold seasons, manufacturers such as Audi, Toyota and Volkswagen declared their EVs can work in extreme environments. As reported in Table 2, the wide ambient temperature range where the TMSs can operate is defined from a lower limit below -10 °C to an upper limit over 40 °C.

Forecasts already define the perspectives of the future TMS. Academic studies and car manufacturers are spending their resources investigating how to improve the active cooling and warming technology dominant in the automotive market. Thermal conductive adhesives are a possible future and simple implementation for the indirect liquid-based TMSs for increasing the contact surface between the cold plate and the battery pack. Other studies are investigating new fluids, as dielectric oils, liquid metals and nanofluids to increase the thermal conductivity of the fluid in substitution of classical mixtures of water and glycol. Dielectric oils open a new scenario in which immersion cooling systems will spread out also in vehicles different from sports cars (such as McLaren Speedtail) to avoid all the issues of an intermediate heat exchanger between fluid and battery. Despite that, in recent years there were manufacturers, as BMW, which developed EVs characterized by refrigerant-based TMSs. For this reason, a return of this technique is not to be excluded for the next generation of electric cars.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

Acknowledgements

This article is part of the project ‘National Centre for Sustainable Mobility’ (cod. CN00000023 - CUP D43C22001190001) - funded by the National Recovery and Resilience Plan – Spoke 2 “Sustainable Road Vehicle” - Italian Ministry of University and Research.

References

- [1] European Parliament, EU ban on sale of new petrol and diesel cars from 2035 explained, 2022. <https://www.europarl.europa.eu/news/en/headlines/economy/20221019STO44572/eu-ban-on-sale-of-new-petrol-and-diesel-cars-from-2035-explained> (accessed February 13, 2023).
- [2] K. Ogura, M.L. Kolhe, Battery technologies for electric vehicles, in: *Electric Vehicles: Prospects and Challenges*, Elsevier Inc., 2017, pp. 139–167, <https://doi.org/10.1016/B978-0-12-803021-9.00004-5>.
- [3] H.M. Ali, Thermal management systems for batteries in electric vehicles: A recent review, *Energy Reports*. 9 (2023) 5545–5564, <https://doi.org/10.1016/j.egy.2023.04.359>.
- [4] David. Linden, T.B. Reddy, *Handbook of batteries*, McGraw-Hill, 2002.

- [5] S. Shahid, M. Agelin-Chaab, A review of thermal runaway prevention and mitigation strategies for lithium-ion batteries, *Energy Conversion and Management*. x. 16 (2022), <https://doi.org/10.1016/j.ecmx.2022.100310>.
- [6] P. Sun, R. Bisschop, H. Niu, X. Huang, A Review of Battery Fires in Electric Vehicles, *Fire Technol.* 56 (2020) 1361–1410, <https://doi.org/10.1007/s10694-019-00944-3>.
- [7] Regione Emilia-Romagna, Veicoli elettrici e ibridi: quarantena precauzionale di 15 giorni, (2023). <https://www.regione.emilia-romagna.it/alluvione/aggiornamenti/2023/maggio/veicoli-elettrici-e-ibridi-quarantena-precauzionale-di-15-giorni> (accessed July 7, 2023).
- [8] X. Hu, Y. Zheng, D.A. Howey, H. Perez, A. Foley, M. Pecht, Battery warm-up methodologies at subzero temperatures for automotive applications: Recent advances and perspectives, *Prog Energy Combust Sci.* 77 (2020), <https://doi.org/10.1016/j.pecs.2019.100806>.
- [9] G. Zhao, X. Wang, M. Negnevitsky, C. Li, An up-to-date review on the design improvement and optimization of the liquid-cooling battery thermal management system for electric vehicles, *Appl Therm Eng.* 219 (2023), <https://doi.org/10.1016/j.applthermaleng.2022.119626>.
- [10] X. Lin, K. Khosravi, X. Hu, J. Li, W. Lu, Lithium Plating Mechanism, Detection, and Mitigation in Lithium-Ion Batteries, *Prog Energy Combust Sci.* 87 (2021), <https://doi.org/10.1016/j.pecs.2021.100953>.
- [11] A. Pesaran, S. Santhanagopalan, G.-H. Kim, Addressing the Impact of Temperature Extremes on Large Format Li-Ion Batteries for Vehicle Applications (Presentation), NREL (National Renewable Energy Laboratory), 2013. <https://www.nrel.gov/docs/fy13osti/58145.pdf> (accessed October 13, 2023).
- [12] Y. Ji, Y. Zhang, C.-Y. Wang, Li-Ion Cell Operation at Low Temperatures, *J Electrochem Soc.* 160 (2013) A636–A649, <https://doi.org/10.1149/2.047304jes>.
- [13] L. He, H. Jing, Y. Zhang, P. Li, Z. Gu, Review of thermal management system for battery electric vehicle, *J Energy Storage.* 59 (2023), <https://doi.org/10.1016/j.est.2022.106443>.
- [14] G. Zhao, X. Wang, M. Negnevitsky, H. Zhang, A review of air-cooling battery thermal management systems for electric and hybrid electric vehicles, *J Power Sources.* 501 (2021), <https://doi.org/10.1016/j.jpowsour.2021.230001>.
- [15] A.A.H. Akinlabi, D. Solyali, Configuration, design, and optimization of air-cooled battery thermal management system for electric vehicles: A review, *Renewable Sustainable Energy Rev.* 125 (2020), <https://doi.org/10.1016/j.rser.2020.109815>.
- [16] C. Yang, H. Xi, M. Wang, Structure optimization of air cooling battery thermal management system based on lithium-ion battery, *J Energy Storage.* 59 (2023), <https://doi.org/10.1016/j.est.2022.106538>.
- [17] X. Shen, T. Cai, C. He, Y. Yang, M. Chen, Thermal analysis of modified Z-shaped air-cooled battery thermal management system for electric vehicles, *J Energy Storage.* 58 (2023), <https://doi.org/10.1016/j.est.2022.106356>.
- [18] Z. Xu, G. Yu, T. Zhang, R. Wang, Cooling performance of battery pack as affected by inlet position and inlet air velocity in electric vehicle, *Case Studies in Thermal Engineering.* 39 (2022), <https://doi.org/10.1016/j.csite.2022.102382>.
- [19] F. Zhang, M. Yi, P. Wang, C. Liu, Optimization design for improving thermal performance of T-type air-cooled lithium-ion battery pack, *J Energy Storage.* 44 (2021), <https://doi.org/10.1016/j.est.2021.103464>.
- [20] J. Jaguemont, J. Van Mierlo, A comprehensive review of future thermal management systems for battery-electrified vehicles, *J Energy Storage.* 31 (2020), <https://doi.org/10.1016/j.est.2020.101551>.
- [21] J. Wu, G. Zhou, M. Wang, A comprehensive assessment of refrigerants for cabin heating and cooling on electric vehicles, *Appl Therm Eng.* 174 (2020), <https://doi.org/10.1016/j.applthermaleng.2020.115258>.
- [22] M. Larrañaga-Ezeiza, G. Vertiz, P.F. Arroiabé, M. Martínez-Agirre, J. Berasategi, A novel direct liquid cooling strategy for electric vehicles focused on pouch type battery cells, *Appl Therm Eng.* 216 (2022), <https://doi.org/10.1016/j.applthermaleng.2022.118869>.
- [23] P. He, H. Lu, Y. Fan, H. Ruan, C. Wang, Y. Zhu, Numerical investigation on a lithium-ion battery thermal management system utilizing a double-layered I-shaped channel liquid cooling plate exchanger, *Int. J. Therm. Sci.* 187 (2023), <https://doi.org/10.1016/j.ijthermalsci.2023.108200>.
- [24] J. Guo, F. Jiang, A novel electric vehicle thermal management system based on cooling and heating of batteries by refrigerant, *Energy Convers Manag.* 237 (2021), <https://doi.org/10.1016/j.enconman.2021.114145>.
- [25] A. Verma, D. Rakshit, Performance analysis of PCM-fin combination for heat abatement of Li-ion battery pack in electric vehicles at high ambient temperature, *Therm. Sci. Eng. Prog.* 32 (2022), <https://doi.org/10.1016/j.tsep.2022.101314>.
- [26] R. Youssef, M.S. Hosen, J. He, M. Al-Saadi, J. Van Mierlo, M. Bercibar, Novel design optimization for passive cooling PCM assisted battery thermal management system in electric vehicles, *Case Stud. Therm. Eng.* 32 (2022), <https://doi.org/10.1016/j.csite.2022.101896>.
- [27] M. Bernagozzi, A. Georgoulas, N. Miché, M. Marengo, Heat pipes in battery thermal management systems for electric vehicles: A critical review, *Appl Therm Eng.* 219 (2023), <https://doi.org/10.1016/j.applthermaleng.2022.119495>.
- [28] H. Behi, D. Karimi, M. Behi, J. Jaguemont, M. Ghanbarpour, M. Behnia, M. Bercibar, J. Van Mierlo, Thermal management analysis using heat pipe in the high current discharging of lithium-ion battery in electric vehicles, *J Energy Storage.* 32 (2020), <https://doi.org/10.1016/j.est.2020.101893>.
- [29] H. Yang, M. Li, Z. Wang, B. Ma, A compact and lightweight hybrid liquid cooling system coupling with Z-type cold plates and PCM composite for battery thermal management, *Energy.* 263 (2023), <https://doi.org/10.1016/j.energy.2022.126026>.
- [30] Y. Wang, X. Zhang, Z. Chen, Low temperature preheating techniques for Lithium-ion batteries: Recent advances and future challenges, *Appl Energy.* 313 (2022), <https://doi.org/10.1016/j.apenergy.2022.118832>.
- [31] S. Wu, R. Xiong, H. Li, V. Nian, S. Ma, The state of the art on preheating lithium-ion batteries in cold weather, *J Energy Storage.* 27 (2020), <https://doi.org/10.1016/j.est.2019.101059>.
- [32] Y. Ji, C.Y. Wang, Heating strategies for Li-ion batteries operated from subzero temperatures, *Electrochim Acta.* 107 (2013) 664–674, <https://doi.org/10.1016/j.electacta.2013.03.147>.
- [33] L. Zhang, W. Fan, Z. Wang, W. Li, D.U. Sauer, Battery heating for lithium-ion batteries based on multi-stage alternative currents, *J Energy Storage.* 32 (2020), <https://doi.org/10.1016/j.est.2020.101885>.
- [34] M. Luo, X. Lin, J. Feng, Z. Ling, Z. Zhang, X. Fang, Fast self-preheating system and energy conversion model for lithium-ion batteries under low-temperature conditions, *J Power Sources.* 565 (2023), <https://doi.org/10.1016/j.jpowsour.2023.232897>.
- [35] H. Zhong, F. Lei, W. Zhu, J. Chen, An adaptive low-temperature mutual pulse heating method based on multiplexing converters for power-redistributable lithium-ion battery pack, *J Energy Storage.* 67 (2023), <https://doi.org/10.1016/j.est.2023.107441>.
- [36] C.Y. Wang, G. Zhang, S. Ge, T. Xu, Y. Ji, X.G. Yang, Y. Leng, Lithium-ion battery structure that self-heats at low temperatures, *Nature.* 529 (2016) 515–518, <https://doi.org/10.1038/nature16502>.
- [37] C.-Y. Wang, T. Xu, S. Ge, G. Zhang, X.-G. Yang, Y. Ji, A Fast Rechargeable Lithium-Ion Battery at Subfreezing Temperatures, *J Electrochem Soc.* 163 (2016) A1944–A1950, <https://doi.org/10.1149/2.0681609jes>.
- [38] M.M. Hamed, A. El-Tayeb, I. Moukhtar, A.Z. El Dein, E.H. Abdelhameed, A review on recent key technologies of lithium-ion battery thermal management: External cooling systems, *Results Eng.* 16 (2022), <https://doi.org/10.1016/j.rineng.2022.100703>.
- [39] M. Shahjalal, T. Shams, M.E. Islam, W. Alam, M. Modak, S. Bin Hossain, V. Ramadesigan, M.R. Ahmed, H. Ahmed, A. Iqbal, A review of thermal management for Li-ion batteries: Prospects, challenges, and issues, *J Energy Storage.* 39 (2021), <https://doi.org/10.1016/j.est.2021.102518>.
- [40] Z. Zhang, S. Liu, L. Tian, Thermodynamic analysis of air cycle refrigeration system for Chinese train air conditioning, *Syst. Eng. Proc.* 1 (2011) 16–22, <https://doi.org/10.1016/j.sepro.2011.08.004>.
- [41] X. Xu, J.J. Zhu, H. Zhang, Z. Yi, X. Wang, G. Zhao, Low cost energy-efficient preheating of battery module integrated with air cooling based on a heat spreader plate, *Appl Therm Eng.* 232 (2023), <https://doi.org/10.1016/j.applthermaleng.2023.121024>.
- [42] Q. Wang, B. Jiang, B. Li, Y. Yan, A critical review of thermal management models and solutions of lithium-ion batteries for the development of pure electric vehicles, *Renewable Sustainable Energy Rev.* 64 (2016) 106–128, <https://doi.org/10.1016/j.rser.2016.05.033>.
- [43] W. Zuo, J. Li, Y. Zhang, Q. Li, Effects of flow direction in mini U-channel cold plates on thermal performance of a prismatic LiMn2O4 battery, *J Therm Anal Calorim.* 148 (2023) 3689–3699, <https://doi.org/10.1007/s10973-022-11935-y>.
- [44] W. Zuo, Y. Zhang, J. E, J. Li, Q. Li, G. Zhang, Performance comparison between single S-channel and double S-channel cold plate for thermal management of a prismatic LiFePO4 battery, *Renew Energy.* 192 (2022) 46–57, <https://doi.org/10.1016/j.renene.2022.04.116>.
- [45] Y. Zhang, W. Zuo, J. E, J. Li, Q. Li, K. Sun, K. Zhou, G. Zhang, Performance comparison between straight channel cold plate and inclined channel cold plate for thermal management of a prismatic LiFePO4 battery, *Energy.* 248 (2022), <https://doi.org/10.1016/j.energy.2022.123637>.
- [46] W. Zuo, Y. Zhang, J. E, Y. Huang, Q. Li, K. Zhou, G. Zhang, Effects of multi-factors on performance of an improved multi-channel cold plate for thermal management of a prismatic LiFePO4 battery, *Energy* 261 (2022), <https://doi.org/10.1016/j.energy.2022.125384>.
- [47] D. Li, W. Zuo, Q. Li, G. Zhang, K. Zhou, J. E, Effects of pulsating flow on the performance of multi-channel cold plate for thermal management of lithium-ion battery pack, *Energy.* 273 (2023), <https://doi.org/10.1016/j.energy.2023.127250>.
- [48] H. Selvnes, Y. Allouche, R.I. Manescu, A. Hafner, Review on cold thermal energy storage applied to refrigeration systems using phase change materials, *Thermal Science and Engineering Progress.* 22 (2021), <https://doi.org/10.1016/j.tsep.2020.100807>.
- [49] E. Oro, A. de Gracia, A. Castell, M.M. Farid, L.F. Cabeza, Review on phase change materials (PCMs) for cold thermal energy storage applications, *Appl Energy.* 99 (2012) 513–533, <https://doi.org/10.1016/j.apenergy.2012.03.058>.
- [50] J.R. Patil, P.A. Mahanwar, E. Sundaramoorthy, G.S. Mundhe, A review of the thermal storage of phase change material, morphology, synthesis methods, characterization, and applications of microencapsulated phase change material, *Journal of Polymer Engineering.* 43 (2023) 354–375, <https://doi.org/10.1515/jpolyeng-2022-0254>.
- [51] Z. Huo, X. Hong, Y. Li, Z. Chen, D. Ruan, Numerical study of paraffin and glass fiber composites for thermal management of lithium-ion battery packs, (2023).
- [52] D. Pevec, J. Babic, A. Carvalho, Y. Ghiassi-Farrokhfal, W. Ketter, V. Podobnik, A survey-based assessment of how existing and potential electric vehicle owners perceive range anxiety, *J Clean Prod.* 276 (2020), <https://doi.org/10.1016/j.jclepro.2020.122779>.
- [53] Audi MediaCenter, Battery and thermal management, (2023). <https://www.audi-mediacenter.com/en/emotive-design-and-revolutionary-technologythe-audi-e-t-ron-gt-quattro-and-the-audi-rs-e-tron-gt-13655/battery-and-thermal-management-13784> (accessed June 27, 2023).
- [54] Electric Vehicle Database, Electric Vehicle Database, (2023). <https://ev-database.org/> (accessed June 27, 2023).

- [55] TeamSpeed, McLaren Speedtail Has Highest Battery Power Among Road Cars, (2020). <https://teamspeed.com/articles/mclaren-speedtail-has-highest-battery-power-among-road-cars/> (accessed June 27, 2023).
- [56] C. Roe, X. Feng, G. White, R. Li, H. Wang, X. Rui, C. Li, F. Zhang, V. Null, M. Parkes, Y. Patel, Y. Wang, H. Wang, M. Ouyang, G. Offer, B. Wu, Immersion cooling for lithium-ion batteries – A review, *J Power Sources*. 525 (2022), <https://doi.org/10.1016/j.jpowsour.2022.231094>.
- [57] Newsroom Porsche, The battery: Sophisticated thermal management, 800-volt system voltage, (n.d.). <https://newsroom.porsche.com/en/products/taycan/battery-18557.html> (accessed June 27, 2023).
- [58] M. Stuparyk, BMW i4: Preview, (n.d.). <https://www.ampacity.club/blog/bmw-i4> (accessed June 29, 2023).
- [59] Green Car Congress, More details on the Mercedes-Benz EQS, (2021). <https://www.greencarcongress.com/2021/04/20210404-eqs.html> (accessed July 2, 2023).
- [60] InsideEVs, Mercedes-Benz Reveals Technical Specs For EQS Electric Sedan, (2021). <https://insideevs.com/news/498761/mercedes-technical-specs-eqs/> (accessed July 2, 2023).
- [61] Electrek, Mercedes-Benz unveils EQS specs: up to 478 miles of range on big 108 kWh battery pack, (2021). <https://electrek.co/2021/04/05/mercedes-benz-eqs-specs-range-battery-pack/> (accessed July 2, 2023).
- [62] Tesla, Model Y, (n.d.). https://www.tesla.com/en_gb/modely (accessed July 1, 2023).
- [63] A. Wray, K. Ebrahimi, Octovalve Thermal Management Control for Electric Vehicle, *Energies* (basel). 15 (2022), <https://doi.org/10.3390/en15176118>.
- [64] N. Mancini, J.S.M. Mardall, J. Kopitz, C.R. O'Donnell, D.F. Hanks, H. Li, Optimal source electric vehicle heat pump with extreme temperature heating capability and efficient thermal preconditioning, *US 2019 / 0070924 A1*, 2019.
- [65] Mobility Engineering, How Nissan's 2023 Ariya EV Keeps Its Cool, (2022). <https://www.mobilityengineeringtech.com/component/content/article/ae/stories/news/47223> (accessed July 2, 2023).
- [66] J. Katamura, K. Hatta, K. Wakabayashi, M. Takagi, N. Todoroki, NISSAN TECHNICAL REVIEW 2022 No.88, 2022.
- [67] Driving electric, Nissan Leaf replacement will be a crossover SUV, (2022). <https://www.drivingelectric.com/nissan/leaf/41411/nissan-leaf-replacement-will-be-a-crossover-suv> (accessed July 2, 2023).
- [68] Toyota Europe Newsroom, The All-New Toyota bZ4X, (2022). <https://newsroom.toyota.eu/the-all-new-toyota-bz4x/> (accessed July 2, 2023).
- [69] Volkswagen Newsroom, ID.family, (n.d.). <https://www.volkswagen-newsroom.com/en/id-family-5002> (accessed July 2, 2023).
- [70] Volkswagen Group of America, The High-Voltage System in the ID.4, 2020.
- [71] H.S. Kang, S. Sim, Y.H. Shin, A numerical study on the light-weight design of PTC heater for an electric vehicle heating system, *Energies* (basel). 11 (2018), <https://doi.org/10.3390/en11051276>.
- [72] M.D. Zolot, K.J. Kelly, M. Keyser, M. Mihalic, A.A. Pesaran, A. Hieronymus, Thermal Evaluation of the Honda Insight Battery Pack, in: U.S. Department of Energy Laboratory, 2001.
- [73] S. Yang, C. Ling, Y. Fan, Y. Yang, X. Tan, H. Dong, A review of lithium-ion battery thermal management system strategies and the evaluate criteria, *Int J Electrochem Sci*. 14 (2019) 6077–6107. <https://doi.org/10.20964/2019.07.06>.
- [74] J. Edmondson, Thermal Management for Electric Vehicles 2023-2033, 2023. <https://www.idtechex.com/en/research-report/thermal-management-for-electric-vehicles-2023-2033/909> (accessed October 12, 2023).
- [75] Y. Deng, C. Feng, J. E. H. Zhu, J. Chen, M. Wen, H. Yin, Effects of different coolants and cooling strategies on the cooling performance of the power lithium ion battery system: A review, *Appl Therm Eng*. 142 (2018) 10–29, <https://doi.org/10.1016/j.applthermaleng.2018.06.043>.
- [76] J. Patel, A. Soni, D.P. Barai, B.A. Bhanvase, A minireview on nanofluids for automotive applications: Current status and future perspectives, *Appl Therm Eng*. 219 (2023), <https://doi.org/10.1016/j.applthermaleng.2022.119428>.
- [77] J. Li, W. Zuo, J. E, Y. Zhang, Q. Li, K. Sun, K. Zhou, G. Zhang, Multi-objective optimization of mini U-channel cold plate with SiO₂ nanofluid by RSM and NSGA-II, *Energy*. 242 (2022), <https://doi.org/10.1016/j.energy.2021.123039>.
- [78] M.S. Liu, M.C.C. Lin, C.Y. Tsai, C.C. Wang, Enhancement of thermal conductivity with Cu for nanofluids using chemical reduction method, *Int J Heat Mass Transf*. 49 (2006) 3028–3033, <https://doi.org/10.1016/j.ijheatmasstransfer.2006.02.012>.
- [79] BMW U.S. Press Information, The new 2017 BMW i3 (94 Ah): More range paired to high-level dynamic performance, 2016. https://www.press.bmwgroup.com/usa/article/detail/T0259560EN_US/the-new-2017-bmw-i3-94-ah--more-range-paired-to-high-level-dynamic-performance?language=en_US (accessed October 12, 2023).
- [80] D. Zhao, G. Tan, A review of thermoelectric cooling: Materials, modeling and applications, *Appl Therm Eng*. 66 (2014) 15–24, <https://doi.org/10.1016/j.applthermaleng.2014.01.074>.
- [81] Z. Yi, P. Wei, H. Zhang, H. Sun, S. Zeng, H. Yu, Wide range temperature thermal performance of power battery module with double-sided thermoelectric device system with high energy efficiency, *Appl Therm Eng*. 227 (2023), <https://doi.org/10.1016/j.applthermaleng.2023.120375>.