Electric Vehicle Enhanced Range, Lifetime And Safety Through INGenious battery management

D8.14 – White Paper 11

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TABLE OF CONTENTS

1 White paper: Introduction

The EVERLASTING project (http://everlasting-project.eu/) will develop innovative technologies to improve the reliability, lifetime and safety of lithium-ion batteries by developing more accurate and standardized battery monitoring and management systems. This allows predicting the battery behavior in all circumstances and over its full lifetime and enables pro-active and effective management of the battery. This leads to more reliability and safety by preventing issues rather than mitigating them.

Among management systems, the thermal management of a battery pack is a very important point. This white paper focusses on the different existing technologies and approaches with potential for the future.

2 White paper 11: Battery thermal management

In this white paper, we will discuss the upcoming questions for thermal management of lithium-ion battery (LIB) packs:

- Why is it necessary?
- Existing technologies
- Potential technologies
- Pros and cons

2.1 Introduction

In earlier times, thermal management of a LIB pack was not considered as a crucial point in its whole design. A Li-ion battery is supposed to be operational between -20°C and around 60°C. Considering it is "roughly" the range of ambient temperature around the world, it was commonly admitted that thermal considerations were not crucial and the main sizing considerations were only linked to electrical performances of the battery pack.

When an electrical current is applied to a battery in case of charging or discharging, heat is generated in the battery due to losses and therefore the temperature of the pack increases. Meanwhile, a vehicle is also submitted to external temperatures, which can strongly vary from one country to another, from one season to another or between day and night. Therefore, the temperature of the battery is affected by the electrical load and by the ambient conditions.

2.2 Ageing considerations

The loss of performances (i.e. autonomy) of some electrical vehicles over time could be ascribed to thermal causes. In literature, we can easily find articles about calendar and cycling effects on the loss of capacity depending on the temperature, the state of charge (SOC), variation of SOC and C-rate.

These ageing aspects are out of the scope of this white paper, but they are the main reasons for which thermal management is required. This aspect will become more and more important with time since:

- batteries will become larger to achieve more range,
- causing internal energy to be higher and upcoming ultra-fast charging will cause more losses and therefore more heat.

3 Common considerations and main constraints

It is common knowledge, that there is an optimal range of temperature for a LIB pack to be respected in order to optimise its lifetime and to limit risks of thermal abuse. Depending on the chemistries and the literature sources, it varies between 15°C-35°C [1] or 25°C-40°C [2].

At the same time, a limited thermal difference from one cell to another is also commonly accepted: 5°C [3]. One must be aware that these values are always considered as reference ones, but specific ageing tests should be carried out for a given battery chemistry. Different battery thermal managements are developed for electric vehicles and hybrid ones. From thermal point of view, it would be quite easy to respect these considerations, but thermal management means additional components and therefore added mass and costs.

Considering stationary applications, added mass is not a real problem since it does not affect autonomy and the battery is less affected by external working conditions.

For transport application, it is quite different, and a compromise has to be found between thermal efficiency and impact on the in-board energy. Focusing on the EVERLASTING specification, the admitted loss of energy density due to the added mass was limited to 5%, which corresponds to an allowed added mass of 15kg.

4 Existing technologies

First of all, we distinguish two main categories for heating/cooling solutions [4]:

- Passive: use of the ambient environment only
- Active: a built-in source provides heating/cooling

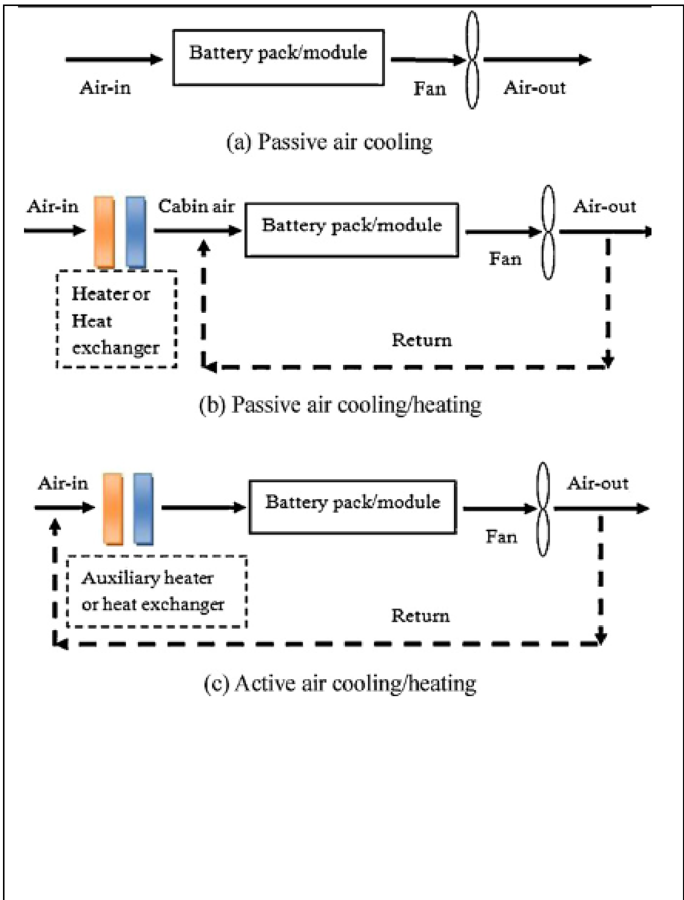


Figure 1: Thermal management using air [4]

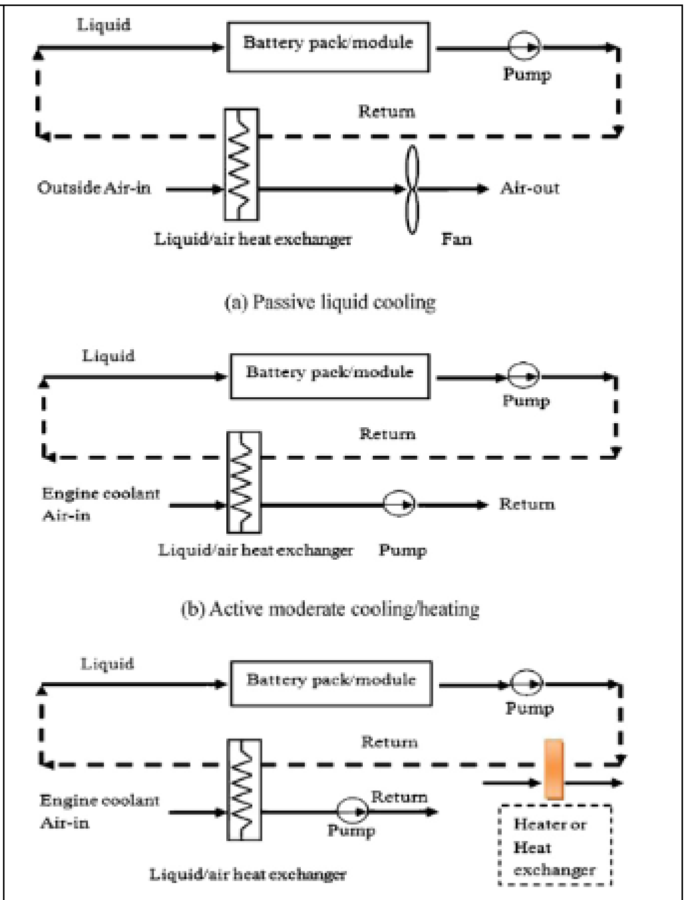


Figure 2: Thermal management using liquid [4]

Further, a classification in four categories based on the used medium is possible:
- Air for heating/cooling/ventilation (See Figure 1)
- Liquid for heating/cooling (See Figure 2)
- Phase change materials (object of EVERLASTING project)
- Combination of different solutions (object of EVERLASTING project)

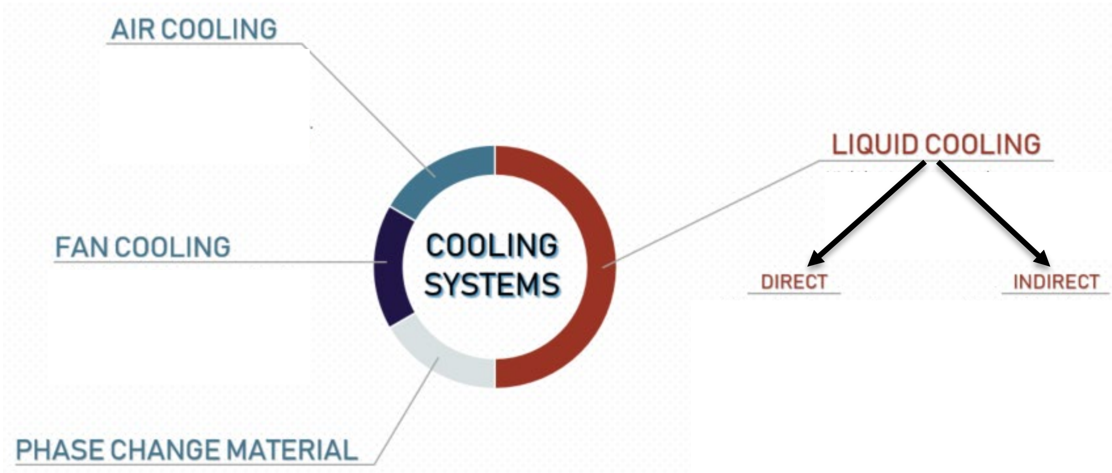


Figure 3 : Summary of potential Battery Thermal Management (BTM) system (with courtesy of Dober [5])

4.1 Air for heating/cooling/ventilation

At first sight, the use of ambient air/cabin air is the simplest way to cool the battery since it is an existing medium easily moved by a fan. Therefore, it was the initial chosen “fluid”. The main troubles with air are its low thermal inertia (i.e. the product between density (kg/m^3) and heat capacity (J/kg/K)) and its low thermal conductivity (W/m/K).

If air flows trough a whole module/pack, it will be warmed quite rapidly due to its low thermal inertia. Becoming hotter and hotter, the first cell will be surrounded by “cold” air wheras the last one will be surrounded by heated air generating a thermal gradient inside the battery module/pack.

Since the thermal conductivity is quite low, the heat exchange coefficient is quite low compared to liquids for example. It leads to an increase of the temperature difference between the wall of the battery and the air to extract the heat, ultimately increasing the average cell temperature. This kind of battery thermal management (BTM) was mainly used on earlier versions of electric cars. There are several articles in literature, in which different technologies are compared with air battery thermal management [5], [6], [7]. This BTM is used for example in Renault ZOE and Nissan Leaf. Although these approaches are called passive systems, it doesn’t mean no energy is used, since fans are being used.

4.2 Liquid for heating/cooling

Liquid heating/cooling is much more efficient in terms of thermal performance compared to air because of its physical properties. In a very simplified way: considering the same heat flux transferred to the fluid and assuming the same increase of fluid temperature, liquid flowrate is equal to air flowrate divided by the ratio of the thermal inertia. Considering a mixture of water and ethylene glycol, volumetric flowrate is divided by a factor around 300 compared to air and mass flowrate is divided by around 3.5, “air-cooling systems need 2 to 3 times more energy than other methods to keep the same average temperature” [8].

4.2.1 Direct contact

The most efficient solution would be to cool all the faces of the battery since the whole heat exchange surface is concerned. In such way, there is no thermal gradient on the outside surface and the electrical connectors could be cooled. However, this technological solution is quite challenging for different reasons:

- Use of dielectric fluids: di-electric oil or liquid-vapour phase change materials;
- Need of specific spacers between batteries if compression is required;
- Potential troubles with tightness.

Since in direct cooling systems batteries are in direct contact with the coolant liquid, fluids have to be dielectric ones. These thermal management systems are currently in the research and development stage, and at the moment no vehicles on the market are equipped with this system. But this is certainly the most promising technology.

4.2.2 Indirect contact

Cold plates (in contact with the bottom of the cells)

For liquid BTM, this is the simplest solution and a quite efficient one. A metallic plate with internal tubes or channels is used to keep a quite constant wall temperature. The plate is commonly made of aluminum to get a uniform temperature. Few tubes are brazed within this plate and coolant flows inside the tubes. With such technology, the thick aluminum plate could be used to "stand" the weight of the cells and would be used as a part of the external casing of the whole pack. Depending on the type of the cells, it may be necessary to add a seal pad between the bottom of the cells and the plate or a thermal paste to ensure a good thermal contact between materials.

Internal fluid is generally a mixture of water and glycol, the amount of glycol being chosen so that it cannot freeze.

Figure 4: Example of thick plates commonly used in industrial applications

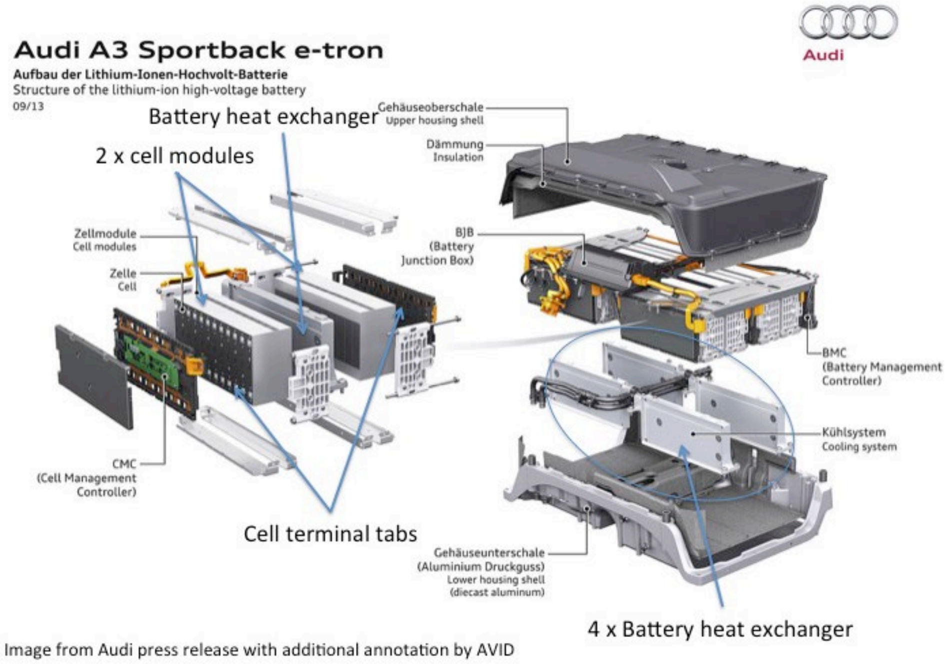


Figure 5 : View of the Audi A3 Sportback e-tron (with courtesy of Avid [9])

The battery heat exchanger is in vertical position but still exchange heat with the bottom of the cells, generating thermal gradient along the height of the cells and has no/limited effect on the tab areas.

Figure 6: Audi e-tron 95 kWh cold plate

At the same time, it is possible to use another technology avoiding water/glycol mixture. The thick cold plate is replaced by a frigorific network of channels. This solution is quite efficient since the cold plate should be at constant temperature if the vaporization of the fluid is well mastered inside the channel (whereas it is not exactly the case with monophasic fluid since it is becoming warmer flowing through the plate). Depending on the country, different types of fluid are used (linked to the local laws about these fluids).

Whatever technology of cold plates is used, heat is extracted from the cells to the plates by thermal conduction, which means internal thermal gradient inside the cells between the top and the bottom. By the way, using quite thick outer aluminum casing for prismatic cells may show constant wall temperature using thermal probe on the outside but it is not the case inside the jellyroll, and it could affect the cell over time.

Heat exchange surface is quite limited, which means a potential quite significant temperature difference between the plate temperature and the top of the cell. If a target temperature is given for example at the top of the cell, the corresponding plate temperature may be quite low and may add additional costs.

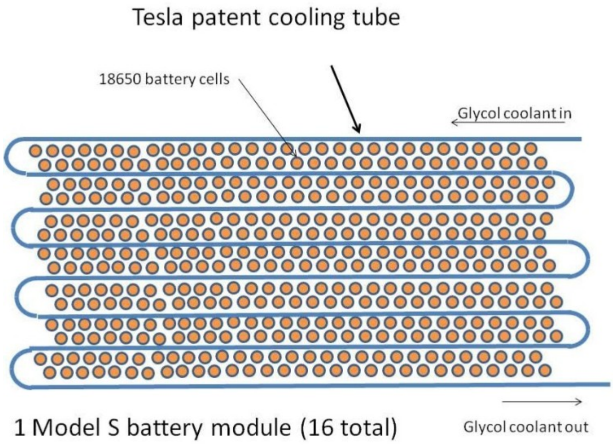
This BTM technology is quite simple and efficient. The pack is the most compact one since using rectangular shapes (pouch or prismatic cells) allows arranging cells one against the other but with a potential risk of runaway propagation in case of thermal abuse of one cell.

Wavy channels (in contact with lateral sides of the cells)

A coolant flows inside a tight channel in contact with the cells. There is no direct contact between the cells and the fluid, since there is a wall. This solution is one of the most efficient solution since it may cool the largest faces of the cells, insuring low thermal gradient inside the cell and low thermal difference (DT) between the coolant and the cell. In such case, of course air or gas are "prohibited" since it makes no sense from thermal point of view. Therefore, with a liquid, heat exchange coefficient is quite high.

TESLA technology

Since cylindrical cells cannot be assembled fitting perfectly, the gaps between cells can be used to insert a cooling tube, as shown below with Tesla technology (Figures 7, 8).



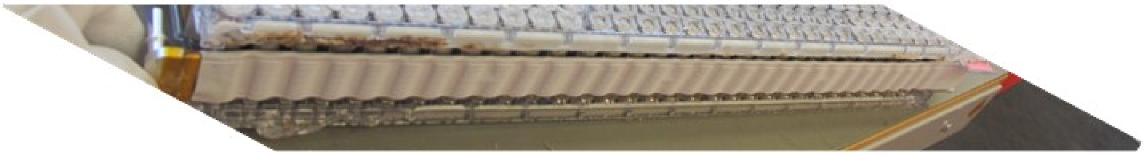


Figure 7 : Indirect BTM used by Tesla

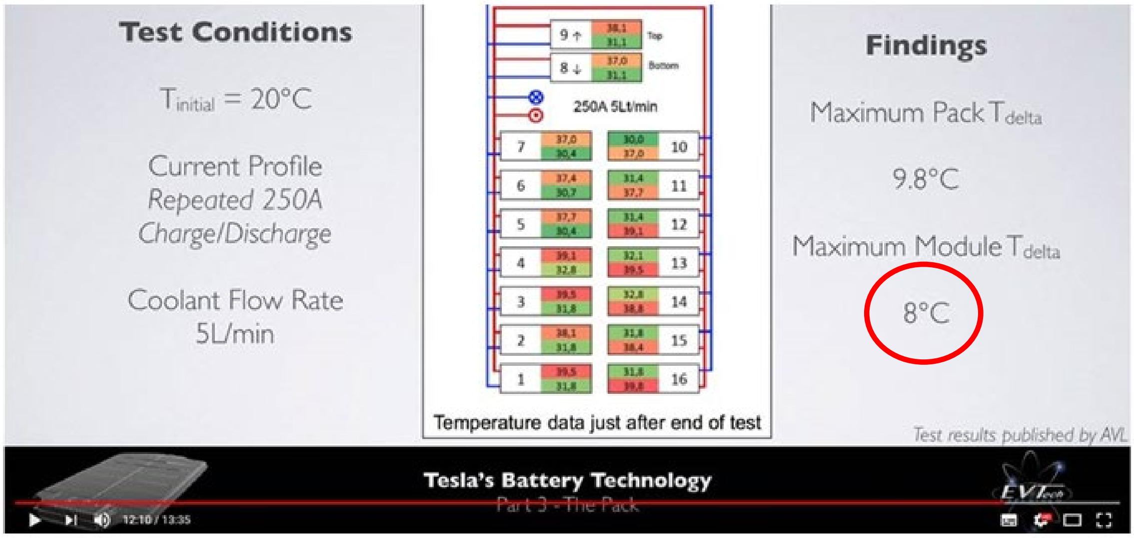


Figure 8 : Thermal map within the pack published by AVL [10]

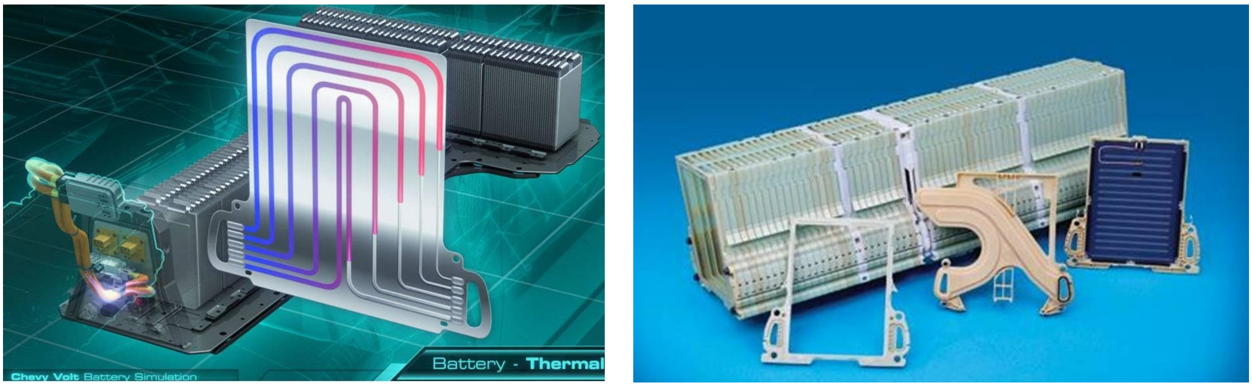


Figure 9 : Active cooling plates between the prismatic cells (Courtesy GM-VOLT Chevrolet)

In Figure 9, there are five individual coolant paths passing through the plate in parallel not in series as the Tesla system does. Each battery pouch (cell) is housed in a plastic "frame". The frames with coolant plates are then stacked longitudinally to make the entire pack. At first sight, this is one of the most efficient battery thermal management but with potential risk of leaks of the coolant.

4.3 PHASE CHANGE MATERIALS

This paragraph is divided into two parts:

- Liquid-vapor phase change materials: since this BTM uses a liquid phase, it can be used either as a fluid flowing through a cold plate or in direct contact with the batteries.

- Solid-liquid phase change materials

4.3.1 LIQUID – VAPOUR

In electronic cooling, local heat flux may be very high: from 20 to 30 W/cm^2 (up to 100 W/cm^2 on specific microprocessors whereas the maximum allowed temperature of these electronic components are around 65°C). Cooling of huge data centers is a real economic challenge since the estimated cost was 7 billion US dollars in USA in 2011.

A new cooling technology has emerged: a quite simple method consists in diving the components directly in a dielectric liquid. This fluid can either remain in monophasic state or change from liquid to vapor state. This process is known as ***pool boiling*** and has a great advantage in terms of performances since heat exchange coefficient grows up during this phase at a quite constant wall temperature (Figure 10). There is no wall resistance and pumping costs are avoided.

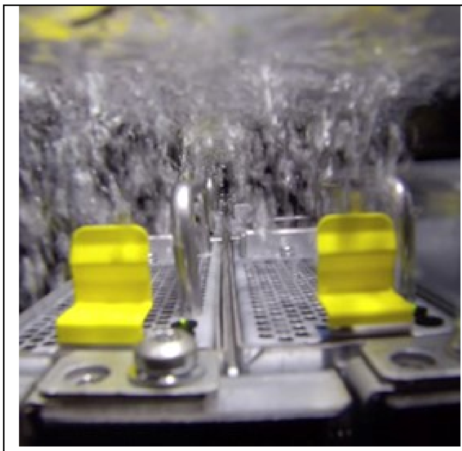


Figure 10 : Example of pool boiling application (with courtesy of 3M [11])

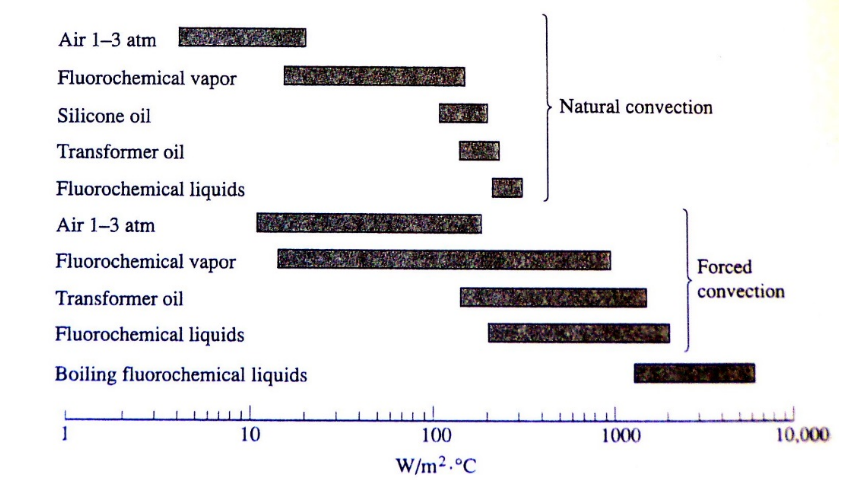


Figure 11 : Heat transfer coefficient orders of magnitude from electronics cooling with various cooling fluids and modes [12].

For battery applications, these kinds of fluids may be very interesting since they can be used in forced convection as a usual dielectric fluid in direct contact with batteries or flowing through a cold plate (indirect contact).

If used in a cold plate, it behaves as an evaporator: This solution is quite efficient, since the cold plate should be at constant temperature, if the vaporization of the fluid is well mastered inside the channel (whereas it is not exactly the case with monophasic fluid, since it is becoming warmer flowing through the plate). Depending on the country, different types of fluid are used (linked to the local laws about these fluids). This kind of technology is used in the BMW i3.

If used in direct contact with batteries (not used at the moment in vehicle applications), there are two main interests:

- Used in forced convection, it behaves like a dielectric fluid flowing through the module in nominal working conditions of the modules/pack.
- In case of abuse conditions, vaporisation of the fluid will generate a high heat exchange coefficient potentially avoiding propagation of a thermal default to the neighbour cells. A very important point to be noticed: even without forced convection of the fluid (i.e. pump off), pool boiling may be activated.

4.3.2 Solid - liquid

Instead of using a liquid-vapor phase change material, also a solid-liquid material can be used. The principle is roughly the same: below and above the melting temperature of phase change material (PCM), heat dissipation of the cells is transferred to the PCM as sensible heat. If melting temperature of the PCM is reached, heat is stored as latent heat of phase change. Since the latent heat is much higher than sensible heat, PCM is able to absorb an important amount of energy without temperature increase as long as the PCM material is not completely melted. The main trouble with common solid-liquid PCM is the way to manage the liquid phase if used with batteries. It is possible to use a micro-composite graphite – PCM matrix which has two main advantages:

- Since the PCM is micro-encapsulated within the graphite, there is no more problem with PCM liquid phase: the graphite behaves as a container.
- Thermal conductivity of the matrix is significantly increased: if used between batteries, heat is thermally dissipated within the matrix and the homogeneity of temperature between cells in the pack is increased.

Figure 12: Different shapes of PCM matrix (with the courtesy of ALLCELL)

Such technology is not yet used in electric vehicles but has been used in an electric scooter application [5]. PCM based battery thermal management is considered as passive solution since it doesn't require specific heat transfer fluid. PCM acts as a heat storage, which spreads heat uniformly in the pack leading to very low temperature difference from one cell to the other. But this heat has to be removed and it requires an additional active/passive BTM.

Therefore, PCM based BTM has to be considered as a hybrid solution:

- Pure passive solution as long as PCM is not completely melted (very low DT within the pack)
- Additional solution generated either during discharge/charge phase or during parking phase to cool down the system.

5 CONCLUSION

Figure 13 summarizes quite well existing and potential BTM systems for EV applications.

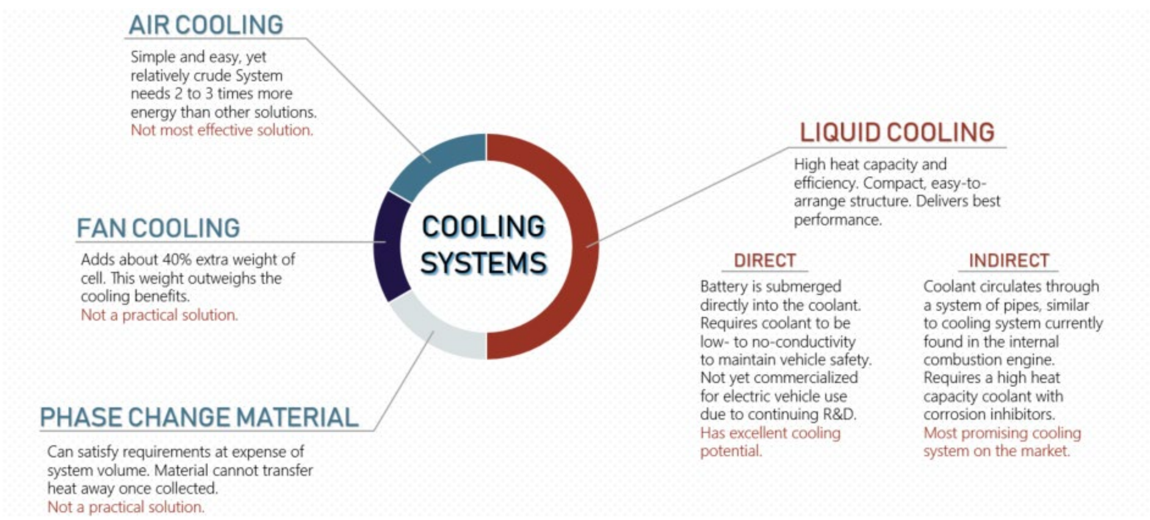


Figure 13 : Summary of potential BTM system (with courtesy of Dober [5])

Active or passive air BTM was mainly used in earlier EVs because it is the simplest solution and the cheapest one. Unfortunately, increase of autonomy (therefore of pack size) and the demand for fast charging will certainly lead to give up this kind of BTM in the years to come. Since air has poor thermal physical properties, high flowrates would be required generating high pressure drop and increased energy costs.

Liquid BTM is widely used mainly in indirect configuration. Flowing either in cold plates (in contact with the bottom of the cells) or in wavy channels (in contact with lateral sides of the cells), common fluids may be used such as mixture of glycol and water or a two-phase fluid (already used in air-conditioning system). A specific fluid loop is dedicated to BTM and its temperature has to be regulated to optimize cell temperature. With liquid BTM, a fluid pump has to be permanently activated, generating energy costs.

Liquid BTM is very efficient from a thermal point of view, but indirect cooling generates thermal gradient inside the cells since contact area are quite limited between the cells and the plate or channel. A direct cooling would be much more efficient if the whole cell is immersed in the fluid. For electrical reason, the fluid has to be di-electric, either monophasic or two-phase fluid. In such configuration, added fluid mass is higher, specific care about the tightness is required and the fluid has to be safe in case of thermal abuse.

BTM based on PCM is widely studied since it may be considered as a pure passive solution for given working conditions as long as PCM is not completely melted. From thermal point of view, it is very efficient in term of thermal discrepancy from one cell to the other: the use of a PCM and graphite matrix allows spreading the dissipated heat homogeneously. In case of thermal abuse of a single cell, it also show interesting behaviour (no propagation to the neighbour cells) [13]. The main troubles are linked to added mass and the need to extract the absorbed heat by an additional system.

Table 1 summarises the pros and the cons of different BTM technologies [4].

Table 1: Trade–off analysis of the battery thermal management [4]

	Air forced	Liquid	Heat pipe	PCM	Thermoelectric	Cold plate
Ease of use	Easy	Difficult	Moderate	Easy	Moderate	Moderate
Integration	Easy	Difficult	Moderate	Easy	Moderate	Moderate
Efficiency	Low	High	High	High	Low	Medium
Temperature drop	Small	Large	Large	Large	Medium	Medium
Temperature distribute	Uneven	Even	Moderate	Even	Moderate	Moderate
Maintenance	Easy	Difficult	Moderate	Easy	Difficult	Moderate
Life	≥20 years	3–5 years	≥20 years	≥20 years	1–3 years	≥20 years
First cost	Low	High	High	Moderate	High	High
Annual cost	Low	High	Moderate	Low	High	Moderate

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