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Research Paper

Water-based Cooling Fluids to Mitigate the Thermal Management Challenges in New Energy Vehicles

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ABSTRACT

Thermal management is considered one of the key enablers for the adoption of New Energy Vehicles. An efficient design of an electrified vehicle's cooling system, be it a HEV, BEV or FCEV, is of major importance to guarantee vehicle lifetime, optimize energy efficiency, enable adequate driving range and allowing high charging speed. Moreover, it is of critical importance for safety.

Compared to internal combustion engine (ICE) vehicles, cooling systems for electrified vehicles have become more complex with increasing integration of a variety of parts. The cooling medium's main function is no longer limited to cooling of the ICE; it also used to conserve and transport heat to essential powertrain parts such as the battery pack, all while electrical safety cannot be jeopardized.

Many recently launched electrified vehicles successfully employ the same water-glycol based cooling liquids that are found in ICE vehicles. In light of future developments such as ultra-fast charging, advances in cooling systems and the cooling liquid are required.

Recently, a clear shift from air cooling towards water-based cooling fluids is witnessed mainly due to the strong beneficial heat transfer properties of water. For direct cooling of fuel cell stacks different changes are demanded since the upper electrical conductivity limit of the aqueous liquid compels the use of new additive technology.

KEYWORDS: Cooling Fluids, Thermal management, Energy Vehicles, Internal combustion Engine (ICE), Battery electric vehicles (BEV), Water-glycol coolants, eMotors, CO_2 emission.

Introduction

Governmental regulations and legislations brought into existence to counteract the effects air pollution and global warming (2015 Paris Agreement) cause the automotive industry to focus on technologies to improve fuel economy and strive to Corporate Average Fuel Economy (CAFE) standards. This reduction is achieved by working on the tailpipe emission of their vehicle fleets (EURO-norms, BS VI emission regulation) and by electrification of their engine park. Where the CAFE regulations are currently under dispute in the US, EU has recently further decreased emission targets for their car fleet, 15% reduction from 2025 and 37.5% reduction from 2030. For vans and light duty trucks, a 15% reduction from 2025 on and 31% reduction from 2030 (EU 2019/631) is put forwards [1]. Heavy duty fleets will target 15% reduction from 2025 on and 30% reduction from 2030 [2]. Those targets combined with an additional incentive mechanism for zero- and low-emission vehicles, further indicates the EU's ambition for a gradual transition towards a zero-emission mobility. In a next step, it is further expanded to have the emission control during operation expanded by the incorporation of the total carbon footprint of vehicle production. The People's Republic of China also has a clear ambition for emission reduction through central government policies such as the Development plan of the NEV industry 2021-2035 [3]. In India, the policy framework for transportation emission reduction is wrapped in the Scheme for Faster Adoption and Manufacturing of Electric Vehicles in India Phase II [4,5].

Previously, the above regulations and policies have led to successful development and application of new technologies, such as Exhaust Gas Recirculation (EGR) for NOx reduction. Moreover, they have been the driver to extensively optimize the efficiency of the internal combustion engine (ICE) by advances in engine design and operating conditions, e.g. by increased operating temperatures [6,7].

Further optimization of the ICE will be part of the solution to reduce emissions, but the gains are likely not sufficient to meet the stringent targets. To comply with regulations, and to ensure a green image, most Original Equipment Manufacturers (OEMs) are electrifying their fleets with unprecedented speed, resulting in a diversification from 48V systems over Hybrid Electrical Vehicle (HEV), Plug-in Hybrid Electrical Vehicle (PHEV), Battery Electrical Vehicle (BEV) and Fuel Cell Electric Vehicles (FCEV).

Although electrified technologies hold high promise to reduce greenhouse gas emissions during operation, the high purchase cost, limited mileage range, a lack of charging facilities, perceived recycling complexity and public opinion are hampering popularity of such vehicles. OEMs as well as governments are still required to encourage adoption through several financial incentives ranging from tax benefits and rebates to investments in (fast-)charging networks or hydrogen filling stations [8]. For example, the FAME India Phase II reduces Goods & Service Tax on electric vehicles (EVs) to 5%, while the Budget 2020 also offered major incentives for buyers of EVs in the form of income-tax rebates on loan. China NEV policies contain tax cuts, purchase subsidies or local policies (low emission zones, exemption from vehicle licensing restriction, priority road access, parking benefits… [9]. As it was shown that removal of such incentives immediately impacts EV sales, different drivers for adoption need to be sought for.

Although regional differences apply, today's public opinion on EVs is mainly formed by familiarity, cost, range, safety and performance. Research has shown that only 1 out of 2 consumers in the US and German car market are familiar with EVs and related technology, which makes that there are significant opportunities for focused marketing or consumer education campaigns to increase awareness and to avoid general misconceptions concerning EV technology among consumers [10]. Since the Li-ion battery is by far the most expensive part of an EV, high driving range is often coupled to increased capital cost of the vehicle, however, the total cost of ownership, which can be highly competitive with ICE vehicles for specific driving profiles or in countries with high fuel costs, is often overlooked by consumers. As battery production costs are expected to further decrease and progressively more electrified vehicle models are launched, options that are more economical are becoming available [10,11]. Furthermore, an EV battery retains its intrinsic value well if maintained properly. When considering circular economy the battery can after its automotive service life, be further employed as stationary battery in energy grid buffers or domestic applications. Simultaneously the recycling technology for Li-ion batteries is progressing fast.

To increase service life of the battery and EV auxiliaries, thermal management of the electric drivetrain is of predominant significance. Moreover, advanced thermal management is of critical importance for battery and vehicle safety, allows for faster charging and is a key factor in vehicle performance and efficiency [12-16].

Results and Discussion

Battery electric vehicles (BEV)

Taking into account thermal management of BEVs, i.e. a vehicle in which the only source of energy comes from the battery pack, 3 main components are in scope: the battery pack itself, the electric motors and the power electronics, while charging rate and cabin comfort also need consideration for a review of the thermal balance.

In a BEV, the battery pack is typically large (25-100 kWh) to accommodate an extended vehicle operating range. A battery pack contains either cylindrical, prismatic or pouch type cells designed for high energy density, made of various Li-ion chemistries (predominantly Lithium Nickel Manganese Cobalt (NMC), Nickel Cobalt Aluminum (NCA) and Lithium Iron Phosphate (LFP)), a Battery Management System (BMS) and a protective housing. To optimize performance and lifetime, the battery pack needs operation in its desired operating temperature range. To accommodate the narrow temperature window, air channels are integrated in the pack design, liquid coolant tubes are fitted inside the pack or the pack is assembled and positioned on top of a plate cooler (Figure 1A,B). Although there are differences in Li-ion battery chemistry, a Li-ion battery is ideally operated between 15° and 35°C. At lower temperatures, electrochemistry is sluggish and high charging speeds should be reduced to avoid Li-plating. The latter, in turn, causes battery capacity loss and may rupture the separator or permeable membrane between the anode and cathode. At higher temperatures, capacity loss may occur due to structural degradation of the electrodes. Moreover, when exceeding the battery working temperature there is a risk for further overheating which in worst case may cause a thermal runaway.

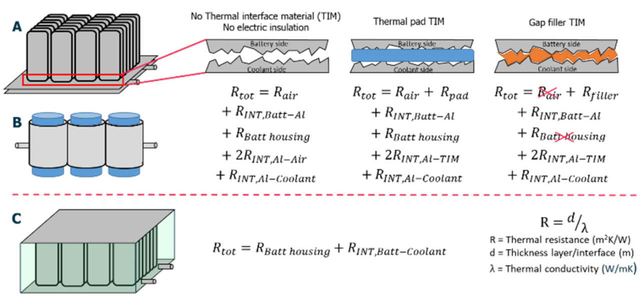

Fig. 1. A: Indirect water-glycol cooling of a battery pack using a bottom plate. Thermal resistance terms indicative of potential gains using TIM. B: Indirect water-glycol cooling of cylindrical cells using a cooling jacket or interleaved tube. C: Direct immersive cooling using a dielectric fluid reduces interfacial thermal resistance.

Even more critical than the operating temperature range, is the temperature homogeneity throughout the battery pack. Temperature gradients in the battery pack cause the separate battery cells to be stressed differently. Since many cells are in series, battery pack performance degradation and capacity loss is therefore accelerated when individual cells undergo different stresses.

Electric motors, power electronics, such as AC-DC, DC-DC convertors, CPUs, and the charging module have less stringent requirements concerning thermal management. Typically, these are operated in a 50-80°C window and require only cooling. Although less critical for safety, cooling efficiency of these electronic parts remains essential for high performance.

The overall efficiency of the electric powertrain is estimated on 80-90%, with heat generation as main energy waste. In absence of an ICE, the heat is sourced and used elsewhere, e.g. to heat the cabin or condition the battery, to ensure energy efficiency of the vehicle and increase driving range. This is especially important considering low ambient temperatures, where the limited electrical energy from the battery is sourced to heat up the cabin and battery using Positive Temperature Coefficient (PTC) heaters or, more efficiently heat pumps.

In practice, all sorts of thermal management architectures are used, ranging from multiple separate cooling loops, to highly integrated systems (Figure 2). The first is typically witnessed when multiple cooling media such as, air, refrigerant gas and liquid coolants are combined, where the thorough integration is almost exclusive for liquid cooling loops in combination with the Heating-Ventilation-Air Conditioning (HVAC) system (chiller). Next to the level, also the method of thermal management integration is still varying among OEMs with use of various heat exchangers or physical mixing of the fluid in the expansion vessel or through trickle valves. In many cases, the thermal management system is optimized for space, cost and performance for a given EV platform. Even regional differences based on average ambient temperatures where, within the same model, the thermal management system is designed to either improve vehicle efficiency at low or high temperatures.

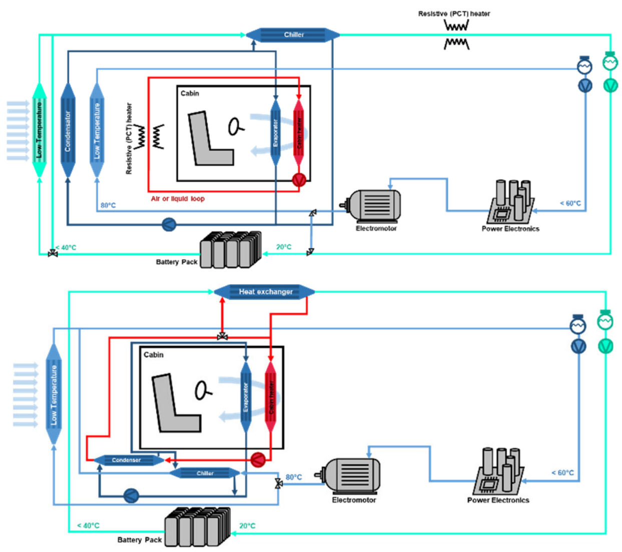

Fig. 2. Top: Schematic overview of a BEV thermal management system with separate battery loop, cabin loop and power electronic loop. Heat is provided by PTC heating elements. The system is coupled with the HVAC system to have auxiliary cooling of the liquid coolant. Bottom: Schematic overview of a BEV thermal management system with integrated battery and power electronic loop (trickle valve system). Auxiliary heating and cooling is provided by a heat pump system.

Fast charging [17] is generally considered as one of the critical enablers for EV market acceptance, yet it is also one of the most demanding conditions towards thermal management. During fast charging, high thermal fluxes up to 25 kW, similar to a small ICE engine, are conceivable while battery overheating needs avoidance.

The above implies that the use of a coolant with high heat transfer coefficient is compulsory to permit significant advances in EV technology. This is further supported by a clear shift in recent model years from cheap and basic cooling systems using ambient air or cooled air towards refrigerants and liquid aqueous based coolants. Water-glycol as a cooling medium ensures temperature homogeneity, easy recuperation of waste heat, high cooling efficiency and DC fast-charging at rates exceeding 20kW while management of flow is well-known and straightforward [12-16]. Selection of the cooling medium, combined with rational design of the cooling system has led to significant advances in performance, efficiency and safety of EVs.

For current applications, standard ICE coolants are employed successfully, yet the coolants face many challenges. It needs to fit in with the many divergent cooling solutions and systems. Many new components are introduced in these systems, such as electric water pumps, chillers and additional heat exchangers, e-Axles, heat pumps and coolant plates or tubes. With new components come new materials eg. plastics, alloys, surface finishes for which the coolant needs full compatibility. For EVs where there is less heat generation, the coolant is used for heating and cooling, potentially has an impact on the compatibility with metal surfaces, elastomers and plastic, due to different additive kinetics. Unfortunately, few information is known today on the corrosive stress in BEV cooling systems or the thermal stress on the coolant and how this compares to former ICE engines. Lower temperature of operation may suggest less harsh condition; however, local phenomena like hot spots, crevice corrosion and corrosion of small protrusions such as convertor pins, should not be neglected. Finally, increase in heat exchanger surface and other narrow passages demands for high stability of a coolant towards flocculation or deposit formation. Some essential current requirements are listed in Table 1.

TABLE 1

Non-exhaustive requirement overview for e-Coolants.

Requirement	Comment
Thermal conductivity	Keeps volume and cycle time low
Heat capacity	Keeps volume low, saves space and
Low viscosity	Minimizes wear and reduces required pumping power
Freeze protection	Protection of parts up to -40°C
Corrosion protection	Including new materials and alloys
Compatibility with elastomers and plastics	New type, more and/or different grades may be used
Electrical conductivity	>2000 µS/cm in standard coolant, for safety reasons, a reduction is desired
Meeting OEM requirements	Few OEMs have a dedicated e-Coolant specification

By means of the thermal conductivity, heat capacity, viscosity and density of a coolant, the heat transfer coefficient can be calculated for a smooth tube with given diameter and length. In Figure 3, the results of calculation of the heat transfer coefficient in laminar (Re < 2300) and turbulent (Re > 2300) flow is given in the range from 0 – 100°C.

$Re < 2300$: Heat transfer coefficient for laminar flow:

$$1.86 * \left(\frac{v}{l * d}\right)^{1/3} * \lambda^{2/3} * (\rho * C_p)^{1/3}$$

$Re > 2300$: Heat transfer coefficient for turbulent flow:

$$\frac{\frac{\mu}{8} * (Re - 1000) * Pr}{1 + 12{,}7 * \frac{\mu}{8}^{1/2} * (Pr^{2/3} - 1)} * \frac{\lambda}{d} \quad \text{Gnielinski equation}$$

$v = Fluid\ flow\ velocity\ \left(\frac{m}{s}\right)$ $\qquad l = Tube\ lenght\ (m)$

$d = Tube\ diameter\ (m)$

$\lambda = Thermal\ Conductivity\ \left(\frac{W}{mK}\right)$

$\rho = Density\ \left(\frac{kg}{m^3}\right)$

$C_p = Specific\ heat\ \left(\frac{J}{kgK}\right)$

$\mu = Friction\ factor$

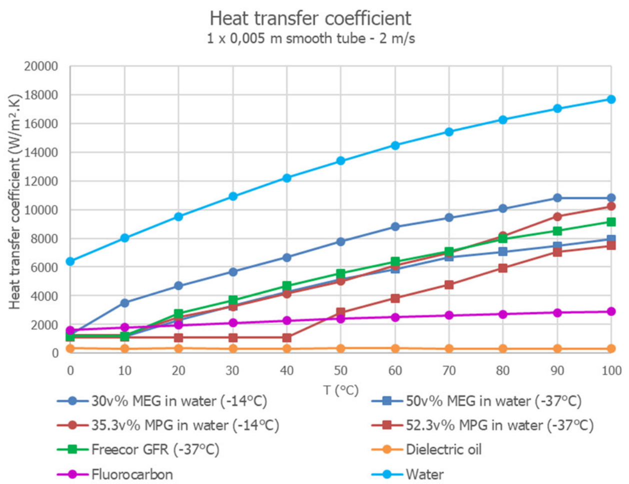

Fig. 3. Heat transfer coefficient of monoethyleneglycol (MEG) and monopropyleneglycol (MPG) mixtures in water compared with a Brine solution coolant (Freecor GFR-37), a fluorocarbon liquid and a standard dielectric transformer oil.

As expected, the superior heat transfer properties of water are clearly witnessed by such calculations, however, for practical use, freezing point depressant such as monoethylene glycol (MEG) or monopropylene glycol (MPG) is required. Due to its physicochemical properties, MEG is preferred over MPG, yet MPG is sometimes preferred for its lower toxicity. In all cases, in the turbulent flow regime, water-glycol mixtures have a higher heat transfer coefficients than dielectric liquid such as fluorocarbon and a standard dielectric transformer oil (Figure 3).

It is commonly recognized that thermal management using current water-glycol systems still limits boundaries for ultra-fast charging and very high performance vehicles. In Figure 4, some commercial vehicles are plotted in a Ragone chart comparing energy density (favors long range, BEV) and power density (favors fast charge/discharge, HEV) of the battery. Considering the coolant type, virtual technological boundaries can be distinguished. Clearly, air cooling is greatly outperformed by refrigerant cooling and water-glycol cooling. Further potential improvement is projected through the application of direct (immersion) cooling of the battery using a dielectric liquid (Figure 1C).

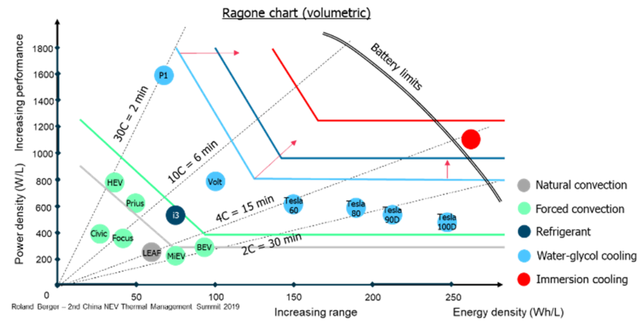

Fig. 4. Ragone chart comparing cooling technologies in commercial vehicles indicating apparent and projected boundaries for charge acceptance. (Adapted from Roland Berger - 2nd China NEV Thermal Management Summit 2019)

Water-glycol coolants used in ICE vehicles coolants are well established in today's BEV due to their high desired heat transfer properties, simplicity, ease of management and excellent vehicle integration (Table 2). Due to the latter two criteria, nowadays, water-glycol is generally preferred over refrigerant cooling which has intrinsically a better cooling performance but is not suitable to heat the battery in colder climates. Furthermore, water condensation on chilled parts and potential pressures up to 20 bar also require dedicated equipment. For the refrigerant as well as for the water/glycol architecture the use of a bottom plate for indirect cooling is required. Water/glycol mixtures need to be electrically insulated from electric components to ensure electrical safety since these are conductive fluids (> 2000 µS/cm). Looking to the balance of advantages and disadvantages water-glycol coolants provide a good compromise and corresponding are well established in today's BEV battery packs in bottom cooling plates (A) for either pouch, prismatic and cylindrical Li-ion cells. Cooling from the bottom has two key benefits. First, since heat flux from the cell is higher in the axial direction of the Li-ion jelly roll (anisotropic thermal conductivity), heat transfer from cell to coolant is optimized when battery cells are placed perpendicular on the bottom plate (Figure 5A)[18]. Second, risk of coolant leak into the battery pack is greatly reduced in case of impact or penetration. In similar fashion, water-glycol coolants are applied in power electronic heat sinks and eMotor cooling jackets. This allows to integrate multiple cooling/heating loops without need of extra heat exchangers and pumps while heat can be efficiently transported between parts.

The requirement to insulate the water-glycol coolant electrically from the battery cells or electrical components causes introduction of several thermal resistance layers hampering the effective heat flux from battery to coolant (Figure 1). In the eMotor, this means only stator cooling combined with an external cooling jacket is found technically applicable, hampering the evolution toward even more power-dense eMotors. Since indirect cooling technology is mature and applied on commercial scale today, many options are being pursued for optimizing the battery to coolant heat transfer in indirect water-glycol cooling setups.

Efficiency loss due to indirect cooling can be partially compensated either by using a suitable thermal interface material (TIM) such as a thermal pad or gap filler to reduce insulating air pockets between battery and coolant. Increasing the thermal conductivity of these TIMs is currently under research and is expected to boost performance from 2 W/mK to at least 5 W/mK, further improving heat transfer from battery pack to cooling plate [19]. Moreover, rational design of the contact surface between battery pack and cooling plate can further reduce thermal resistance between the two parts [20]. Alternatively, cooling jackets or tubes (Figure 1B) can be considered, which further optimize contact between battery and coolant, yet leakage of the conductive coolant can potentially cause more significant issues when integrated within the battery pack. Such approach, the use of interleaved cooling channels, where the coolant is guided between the cells, is largely abandoned for prismatic and pouch but has proven to be efficient for cylindrical cells.

Also for the eMotor, design considerations, such as applying the water-glycol coolant in tubes close to the windings, have shown to have potential to significantly improve the water-glycol cooling performance [21]. Extensive optimization of coolant channels and flow through modelling and artificial intelligence (generative thermal design) are expected to even further boost the performance of indirect cooling systems for each the battery, eMotor and power electronics [22].

To obtain maximal heat transfer, the coolant can be brought as close to the heat source (battery) as possible. Significant reduction of coolant conductivity may enable this to some extent, as it may allow further integration without jeopardizing safety and performance loss through stray eddy currents. Direct contact of the coolant with the electrical component, is the extreme case of this. Although water is a very good dielectric, it is not suitable for direct cooling as risk for contamination with ionic species that increase conductivity, is too high. This makes water inherently unsafe for direct cooling as the high voltage of the battery will cause short-circuits or hydrogen generation due to water electrolysis.

Dielectric liquids such as transformer oils, synthetic esters and fluorocarbons are good electric insulators and have the potential to remove most of the interfacial thermal resistance. These liquids allow immersion cooling of battery cell similar to what is found in high performance data servers (Figure 1C). In eMotors, a dielectric liquid could serve a double role as lubricant and coolant. Although heavily investigated, direct cooling technology is not yet mature. The inferior heat transfer properties of dielectric coolants would imply that larger volumes of these typically more expensive liquids are required. Another consequence is that dielectric liquids are less efficient for transporting heat throughout the vehicle. Furthermore, removing the heat from the dielectric liquid is expected to require a secondary cooling system (HVAC, water-glycol loop) as direct heat transfer from a dielectric coolant to air is inefficient. In the case of transformer oils and synthetic oils, the tradeoff between viscosity and flash point of the liquid, oxidative stability and material compatibility need to be considered. Faulty sealing as result of incompatibility of the fluid with elastomers and plastics may cause penetration of humidity and cause short-circuits. Due to the current low technology readiness level (TRL), increased cost, volume, weight and complexity, direct battery cooling is initially expected to be employed in high performance niche vehicles, but may gain further ground when ultra-fast charging will become the norm [23].

TABLE 2

Conjectured comparison of BEV cooling possibilities. ++ indicating very positive/beneficial to - - very unfavorable. *Oil based dielectric liquid/dielectric fluorocarbon liquid

	Air	Refrigerant	Water-glycol (indirect)	Dielectric* (immersion)
Intrinsic heat transfer	- -	++	+	-
Cooling/heating performance	--	-	+	++
Electrical safety	+	0	-	+/++
Vehicle integration	-	-	++	+
Material compatibility	+	+	+	0
Complexity	++	-	+	-
Cost	++	0	+	0/--
Environmental	++	-	+	0/-

Another interesting means of cooling the battery cell is tab cooling or busbar cooling [18]. As the busbar is typically laser welded to the battery tabs, minor weld imperfections may cause Ohmic losses and consequent heat generation especially at high charge or discharge rates. Both air ducts and dielectric coolants are proposed to cool these potential hotspots. As an extra benefit, the battery tab is in direct contact with the inside of the battery cell in the direction where thermal conductivity of the cell is highest. This results in a highly efficient means of cooling battery cell, for example in ultra-fast charging conditions. Tab cooling with air can be considered as a way to boost the performance of indirect bottom plate cooling with water-glycol. A combination of the latter with dielectric tab cooling (Figure 5B) could be a potential solution to thermal management challenges battery electric solutions are faced with. Such inventive combinations are also envisaged for eMotors, where a combination of an internal dielectric coolant and with a water-glycol jacket holds potential for optimal cooling performance, while maintaining the ideal interface with the rest of the vehicle [24].

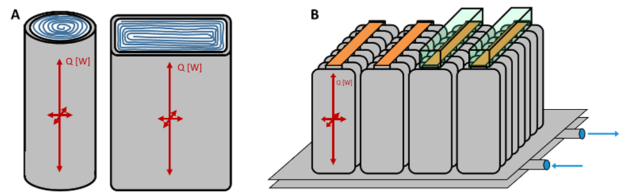

Fig. 5. A: Depiction of the Li-ion jelly roll inside a cylindrical and a prismatic (or pouch) cell. Heat transfer (Q) is generally favored in axial direction. B: Combination of bottom-plate water-glycol cooling and dielectric battery tab cooling.

Hybrid and Plug-in electric vehicles (HEV and PHEV)

Hybrid and Plug-in electric vehicles (HEV and PHEV) are a group of electrified vehicles with very divergent powertrain designs ranging from mild hybrids equipped with a start/stop system to Plug-in hybrids that allow for external charging and have the possibility of full electric drive, though with significant lower range than BEVs. Despite the high variability of set-ups and architectures, all vehicles within the HEV and PHEV classification have a common goal: a reduction of fuel consumption through recuperation of waste energy using efficient electrical supporting aids.

Typically, HEVs and PHEVs are equipped with smaller power-dense batteries (cfr. energy-dense BEV batteries) as they need to cope with very high charge and discharge rates for example during braking or acceleration. Electrical driving range is subordinate to cycle life and battery size is often relatively small as the ICE still serves as main energy source for propulsion. One exception are PHEVs, which may be employed to cruise in full electric mode in congested traffic or low emission zones. For this reason, PHEV batteries trade some power density for energy density and allow up to 10C charge/discharge rates, while HEV batteries may go up to 100C. For PHEVs, charging rates of 50kW are deemed sufficient (overnight charging) while for BEV up to 350 kW charging is desired to get to 4C charging (= 15 mins to full charge) [18]. Range-Extension Electric Vehicles (REEVs) are hybrids where only electrical energy is used for propulsion. Here, a small, energy-efficient combustion engine is used as an auxiliary generator at fixed and optimized rpm to charge the vehicle's battery. In turn, an electrical motor draws power from the battery for acceleration, while braking energy can again be recuperated.

From thermal management point of view, the presence of the combustion engine ensures a permanent source of heat to acclimatize both battery and cabin when required (Figure 6). Furthermore, it may serve as source of mechanical energy for part like the water pump, where BEVs have to rely on 100% electric parts. On the downside, complexity of the powertrain and cooling system is increased with respect to pure ICE vehicles and BEVs. Similar to BEVs, design of battery packs, coolant channels and coolant jackets are subject of investigation to optimize thermal management of battery and electronics, further improving overall vehicle performance and lifetime.

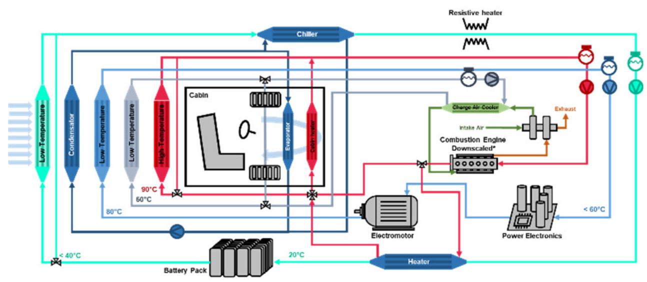

Fig. 6. Schematic overview of a HEV/PHEV thermal management system. In a REEV the combustion engine is downscaled.

Due to its high need for cooling an ICE also limits the options for coolant selection since only water-glycol mixtures are satisfactory in terms of heat transfer. If OEMs opt to keep the cooling loops of ICE, power electronics and battery separated, multiple coolant types can be employed. Witnessed from the use of standard ICE coolant in the field today, benefits are still outweighed by increased complexity and cost. Moreover, when the (P)HEV cooling loops are integrated into one thermal management loop, typically a water-glycol coolant is selected basis the requirements for the ICE to ensure optimal protection of the ICE according to industry or OEM standards.

A novel solution to optimize heat transfer and corrosion protection in HEVs and PHEVs could be a Brine solution coolant (Freecor GFR-37). Comparing a brine solution with the same freezing protection as its water-glycol counterpart, improved heat transfer properties are observed, mainly due to the higher thermal conductivity and density of the brine (Figure 3). This was further confirmed in a 2D simulation of a commercial coolant and a DCDC-Converter equipped with a waterjacket with pins (InDesA GmbH (Ismaning, Germany) using GT suite software). In Table 3 a 9% increase in heat transfer from the component wall is observed, while the outlet temperature is increased with 0.2°C, indicating that the Brine solution coolant has removed more heat from the component than a water-glycol coolant with the same freeing point of -37°C. This improvement comes with the tradeoff of increased pressure drop over the part, and thus increase pumping power requirement.

The same trend is witnessed in a model for a cooling plate structure for the battery module of a Chevrolet Bolt (Table 4), where heat transfer is increased with an estimated 5.6%.

TABLE 3.

Comparison of coolant performance between a commercial water-glycol coolant and a Brine solution using 2D simulation (GT Suite, InDesA) of a DCDC-Convertor. Coolant volume flow = 10l/min; Coolant inlet T = 50°C; Wall T = 60°C, Coolant outlet pressure = 1 bar.

	Commercial water-glycol coolant	Brine solution coolant	Delta
Coolant mass flow rate [kg/s]	0.1728	0.1896	+9.7%
Heat transfer at walls [W]	1676	1829	+9.1%
Pressure drop [Pa]	1586	1729	+9.0%
Coolant outlet temperature [°C]	52.8	53.0	+0.2°C

TABLE 4.

Comparison of coolant performance between a commercial water-glycol coolant and a Brine solution using 2D simulation (GT Suite, InDesA) of a battery pack bottom cooling plate. Coolant volume flow = 20l/min; Coolant inlet T = 25°C; Wall T = 40°C, Coolant outlet pressure = 1 bar

	Commercial water-glycol coolant	Brine solution coolant	Delta
Coolant mass flow rate [kg/s]	0.3552	0.3893	+9.7%
Heat transfer at walls [W]	1405	1483	+5.6%
Pressure drop [Pa]	112.4	122.3	+8.8%
Coolant outlet temperature [°C]	37.62	37.14	+0.42°C

Fuel Cell Electric Vehicles (FCEV)

In a Fuel cell electric vehicle, the ICE of a HEV is replaced by a fuel cell stack to generate electricity from hydrogen (H_2) either as range-extender or as direct means of propulsion (Figure 7). The only by-product of this conversion is water (H_2O) and heat, making FCEVs, together with BEVs, the only commercial zero-emission vehicles known today. Hydrogen, which can be produced by electrolysis of water, has an energy storage medium with a 10-fold higher energy density than batteries (albeit 5-7 times lower than gasoline), making it a viable solution for energy storage of electricity from renewable but intermittent sources such as wind and solar power. Owing to its liquid nature under pressure, it can be transported over large distances without loss of energy, unlike electricity, by use of tankers or pipelines. Moreover, refueling is as fast as for a gasoline or diesel vehicle, while weight is greatly reduced with respect to BEVs. This holds benefits especially for heavy-duty, bus and train applications where centralized hydrogen fueling stations or local hydrogen production can make up for the lack hydrogen infrastructure [7,25].

For mobility applications, Proton Exchange Membrane (PEM) fuel cells, using a Pt or Ru catalyst layer inside the Membrane Electrode Array (MEA) (Figure 8) are almost exclusively used. Herein, the catalyst promotes the electrochemical reaction between hydrogen (H_2) and oxygen (O_2). The catalytic reaction in the PEM fuel cell ($H_2 + O_2 \rightarrow H_2O$ + energy) generally has an efficiency of ± 50%, with the other 50% of the output power being converted to heat. As there is also few to no heat (< 5% vs 33% for ICE) removed through the tailpipe, all generated heat needs to be removed through a cooling system in order to avoid thermal stress on the expensive catalyst layer and the membrane. To cope with the high heat flux from the fuel cell stack, dedicated coolant channels are implemented inside the current collectors or bipolar plates. For small fuel cells (< 5kW) air has been employed as coolant, however for automotive applications (50-150 kW), a water-based coolant is required for its favorable heat transfer properties. As the coolant makes direct contact with the components, electrical safety needs to be ensured. Therefore, the cooling channels are purposely narrow and the water-glycol coolant should be low in electrical conductivity (< 5µS/cm), a combination which also helps to avoid performance loss through leak current.

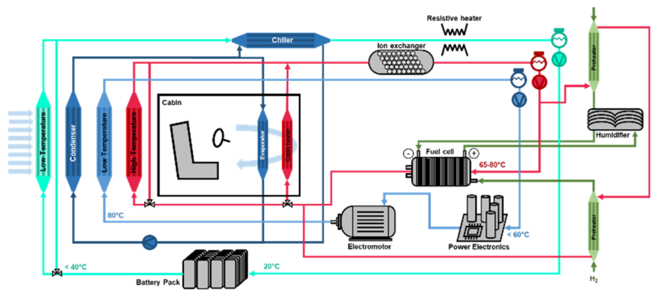

Fig. 7. Schematic overview of a FCEV thermal management system with separate fuel cell loop containing a low-conductive water-glycol coolant.

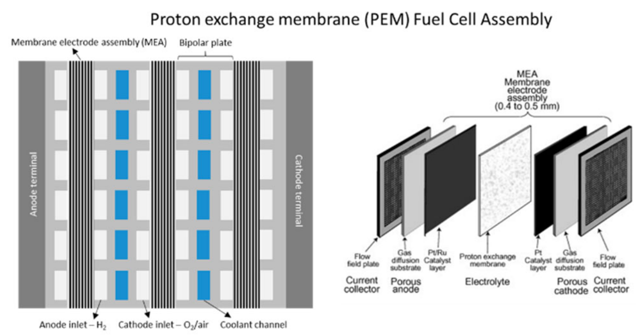

Fig. 8. Proton exchange membrane (PEM) Fuel cell Assembly

The electrical conductivity of the water-based coolant is of utmost importance for safe operation of an FCEV, while low viscosity is preferred for optimal heat transfer and reduced backpressure over the fuel cell stack. To achieve low conductivity, ultra-pure water and high quality glycol are mandatory, while performance additives such as corrosion inhibitors, stabilizers and antioxidants should be inherently non-ionic in nature. Furthermore, cleanliness of the cooling system is key to avoid excessive buildup of conductivity over time. Typically, vacuum brazed aluminum heat exchangers and low-leaching elastomers and thermoplastics are prescribed, while the bipolar plate is increasingly made from inert and corrosion resistant materials ranging from aluminum and stainless steel to titanium and graphite. Heat exchanger surface in the FCEV is generally larger compared to ICE, as a result of the high cooling need of the fuel cell stack, combined with the lower operating temperature of the coolant (60-80°C), making the requirement of radiator cleanliness even more stringent.

As a first measure for electrical safety, the fuel cell cooling loop is generally separated physically from auxiliary cooling loops (eMotor, battery and electronics) where a different cooling fluid (eg. standard ICE coolant) can be employed. To improve the vehicle's energy efficiency, the auxiliary system can be coupled to the fuel cell cooling loop via a heat exchanger to recuperate waste heat for heating the battery or cabin. Next to the physical separation of the fuel cell cooling loop, an ion exchanger is built in to adsorb any ionic impurities from incidental contamination and glycol oxidation. This ensures low conductivity during operation, yet maintenance is required once the adsorption capacity of the ion exchanger is reached.

From the above, it is clear that new additive technology is required for water-glycol low conductive coolants, where focus lies on compatibility with the multitude of materials and devices in the cooling system, on suppression of electrical conductivity during use and on contributing to general cleanliness of the system.

Conclusions

Thermal management of electric vehicles in all its facets is of critical importance for EV adoption as it has a direct impact on performance, safety, convenience of use and thus customer adoption. Recently a clear shift is witnessed where more economical but inefficient air-cooling is traded in for water-glycol cooling, causing major improvements in battery lifetime, charging speed and energy efficiency, which in turn have positively affected performance and range of electric vehicles. Dielectric cooling is believed to have the potential to further extend the cooling capabilities of, especially, BEVs however, many hurdles on system level still need to get resolved to allow large-scale commercial implementation. In addition, the current water/glycol thermal architectures have proven to work, with increased maturity and improvingly efficient solutions. Strategic decisions such as cost-efficient reduction of CO_2 emission (HEV, PHEV) or a more drastic focus on zero-emission (BEV, FCEV) from governments and OEMs will highly influence the type of electrification that will prevail. Together with an initial diversification of the electrified vehicle fleets in the upcoming years, thermal management solutions are also likely to be subject of diversification. Every vehicle or car platform will have its unique optimal thermal solution, be it using indirect or direct cooling using either decoupled or integrated loops, in order to optimize performance, complexity and cost. Technologic breakthroughs such as solid-state batteries or CO_2 capture may become game changers that have the capability to change this diverging trend back into converging, however such technologies have not reached their full potential yet. In the meantime, research and continuous improvement of the current systems, combined with innovative fluids may also converge into thermal management solutions in which performance, complexity and cost are optimized according to OEM strategy.

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