

Review

Thermal Management of Electrified Vehicles—A Review

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Abstract: Vehicle electrification demands a deep analysis of the thermal problems in order to increase vehicle efficiency and battery life and performance. An efficient thermal management of an electrified vehicle has to involve every system of the vehicle. However, it is not sufficient to optimize the thermal behavior of each subsystem, but thermal management has to be considered at system level to optimize the global performance of the vehicle. The present paper provides an organic review of the current aspects of thermal management from a system engineering perspective. Starting from the definition of the requirements and targets of the thermal management system, each vehicle subsystem is analyzed and related to the whole system. In this framework, problems referring to modeling, simulation and optimization are considered and discussed. The current technological challenges and developments in thermal management are highlighted at vehicle and component levels.

Keywords: thermal management; electrified vehicle; thermal modeling; thermal optimization



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1. Introduction

Road transportation has a major role in the production of greenhouse gas (GHG). In fact, according to the European Union Commission, road vehicles have accounted for 17% of the total GHG emissions in the last decade and of the 72% of GHG emission in transportation [1]. Similar figures can be found in the US, where according to EPA (United States Environmental Protection Agency), the transportation sectors were responsible for 29% of GHG emissions in 2019 [2], of which about 80% due to road transportation. In such a contest, more and more stringent regulations are being issued.

Vehicle electrification has the potential to reduce GHG emissions, provided that clean electricity generation is available [3]. Thermal management plays a major role in increasing the efficiency of hybrid, plug-in hybrid and electric vehicles. In fact, most of the energy losses are still related to thermal generation and correctly governing such thermal fluxes can lead to better performances of vehicle subsystems and better occupant comfort. Thermal management is not related only to vehicle performances or comfort. A correct thermal management allows a longer life of components, lightweight and cost reduction.

Traditional internal combustion (IC) vehicles' thermal management is focused only on engine and cabin conditioning. The high working temperature of the engine allows for the use of ambient air for cooling, while its low efficiency provides a large amount of residual heat for cabin warming. Air conditioning is used only for cabin cooling, while dedicated cabin heaters are used only for particular applications, while, in most cases, the residual heat of the engine is sufficient.

Hybrid vehicles (HEV) or plug-in hybrid vehicles (PHEV) require a much more complex thermal management system. In fact, beside engine and cabin, also batteries, motors and power electronics have to be considered. Battery thermal management, in particular, is quite complex due to the limited operative temperature range of the batteries coupled with the requirement of a low temperature gradient. The low maximum temperature of the batteries may require a dedicated cooling system, while the relatively high minimum temperature can lead to the use of heaters for the warm up phase. Motors and power

electronics have temperature requirements different from batteries and IC engine, requiring a dedicated cooling circuit. Especially for PHEV, the use of the engine is limited. As a consequence, limited residual heat is available for cabin heating and a dedicated cabin heater may be required.

Electric vehicles' (EV) thermal management shares most of the challenges of the HEV and PHEV systems with reference to batteries, motor and power electronics. However, particular problems have to be considered too. Recent EV have a very high recharge power. As a consequence, a high temperature increase in the batteries can be expected during charging. Especially in hot climates, battery conditioning may be needed during charging. Cabin heat and cooling is more critical than in other types of vehicles as the energy for both heating and cooling must be provided by the batteries. Cabin conditioning may lead to a large reduction of vehicle range.

Thermal management of electrified vehicles is widely discussed in the literature. Several review papers can be found addressing the problem of the thermal management for vehicle subsystems [4–8] with special reference to batteries [9–22], for the whole vehicle [23–25] or from a modeling perspective [26,27]. The present review aims to provide the designer of the thermal management system the most relevant information about the components, while focusing on the system. Mathematical modeling is also discussed as a necessary tool for system design and optimization.

The thermal management system has the function of providing the best possible thermal condition to the subsystems of the vehicle. Due to vehicle complexity, in the thermal management system design, many different objectives have to be taken into account, often in conflict [26]. In such a situation, to find the best configuration of the thermal management system, the designer has to perform an optimization at system level [28,29]. In fact, in general, a system made up of individually optimized components is not the optimal one. Component interactions have to be taken into account.

The paper is organized as follows. Firstly, brief background is given referring to electrified vehicle subsystems. Then, the thermal management requirements are discussed and its basic architectures are presented. Then, a detailed analysis of the main components of the vehicle are provided describing the related challenges and modeling issues. Finally, the optimization of the thermal management system is considered. The paper is structured as an organic introduction to the wide topic of the thermal management of electrified vehicles. For each of the considered points, pertinent references, including dedicated states of the art, are given to provide the necessary insight to the interested reader.

2. Components Thermal Requirements

In this section, the main thermal requirements of the components used in different types of vehicles are described. This section is meant to provide basic information for the remainder of the paper, thus no specific reference is given. Detailed references will be provided in Section 5 dedicated to each component.

IC Engine. Application: IC, HEV and PHEV (IC = internal combustion engine vehicle, HEV = hybrid electric vehicle, PHEV = plug-in hybrid electric vehicle, EV = electric vehicle). Operative temperature 85–110 °C. The minimum operative temperature has to be reached in the shortest possible time to reduce fuel consumption and to have a heat source for cabin heating. No dedicated heater is usually employed. Engine heating up is sped up by reducing the flow of the coolant until the desired temperature is reached. Under-hood heat retention can be an effective way to speed up the heating up phase when the engine is restarted after a relatively short period of time. The heating up phase can be critical especially for PHEV when the engine can be switched off for most of the time. Due to the high values of the operative temperatures, ambient air cooling is sufficient.

Electric Motor. Application: HEV, PHEV and EV. Operative temperature <60 °C. Electric motors have high efficiency, therefore, a relatively low amount of energy is dissipated by heat, usually not sufficient for cabin heating. The maximum operative temperature is well above the ambient temperature in most of the climates. Therefore, in most cases,

cooling by ambient air is sufficient. However, for extreme climates, an air conditioning system may be required.

Power electronics. Application: HEV, PHEV and EV. Operative temperature $<60\text{ }^{\circ}\text{C}$, special applications may have high temperature electronics with maximum operative temperature above $100\text{ }^{\circ}\text{C}$. In most cases, power electronics has the same temperature requirements of the electric motors. A common cooling circuit for power electronics and motor is usually realized.

Batteries. Application: HEV, PHEV and EV. Operative temperature $20\text{--}40\text{ }^{\circ}\text{C}$ optimal temperature range, $<50\text{ }^{\circ}\text{C}$ to avoid damaging or combustion. Battery overheating has to be avoided not only to achieve the maximum performances from the component, but to prevent the thermal runaway and battery explosion. The temperature gradient across the battery must be minimized. Thermally unbalanced batteries, i.e., with different temperatures between cells or temperature gradients on the cells, show performance degradation and reduced capacity. Low battery temperature has also to be avoided as it leads to degradation, limited power and energy capacity reduction. As the maximum battery temperature can be lower than ambient temperature, conditioned air is required. In some cases, especially for modern batteries with high charging power and current, the conditioning system is required also during the charging period. For low ambient temperature, battery pre-heating may be necessary.

Cabin. Cabin heating and cooling are required for passenger comfort. For cabin cooling, an air conditioning system is used. Cabin heating can be obtained by exploiting the residual heat of other components. In practice, only the engine can provide a sufficient amount of residual heat for an effective cabin heating. For vehicles where the residual heat is not sufficient, mostly PHEV and EV, a heater has to be employed. Cabin conditioning thermal requirements strongly depend on the ambient condition and number of occupants.

In Table 1, the indicative temperature ranges are given for the main components of the vehicle.

Table 1. Indicative working temperature ranges of the most common vehicle systems.

Vehicle System	Temperature Range [$^{\circ}\text{C}$]
IC Engine	85–110
Electric Motor	<60
Power electronics	<60 *
Batteries	20–40 optimal –10–50 to avoid damage
Cabin	Occupant comfort temperature $\sim 20\text{--}25$

* for special applications, temperature above $100\text{ }^{\circ}\text{C}$ can be reached.

3. Thermal System Requirements

For the definition of the architecture of the thermal management system, many factors have to be considered. As mentioned in Section 2, depending on the type of vehicle, different components are present and, consequently, a different thermal management specification. Beside vehicle type, which plays an obvious role, other important factors are the following.

- *Environment.* The place, i.e., the ambient temperature, where the vehicle is used plays an important role in the definition of the required thermal management system [30]. From a battery perspective, the minimum ambient temperature indicates if a pre-heating is necessary. The maximum temperature is important for choosing between a cooling system with ambient air or conditioned air. Maximum temperature is also important for the charging phase. In fact, for hot climates, battery cooling during recharging may be necessary. Referring to cabin temperature control, the minimum temperature can influence the choice of the coolant fluid of the air conditioning and the necessity of a cabin heater.

- *Vehicle mission and performances.* Vehicle mission and performances, in particular range and power, have a direct effect on the heat generated by the driveline components, such as batteries, electric motors and power electronics with consequences on the required cooling system [24].
- *Cold start and travel type.* Temperature when starting the vehicle is critical for consumption and pollution of engines and for the warm up time [31]. Frequent use for short travels causes the engine to function always below the optimal temperature range [32].
- *Driving cycle.* Homologation driving cycles specify defined driving conditions. However, a real-world driving cycle may differ for the specific considered vehicle. Different driving cycles require different optimization of the vehicle and its thermal management system [33,34].
- *Homologation requirements, safety and quality.* The thermal management system must respect homologation requirements, regulations and safety criteria. A quality plan should be also considered to assure the desired performances of the system [18,35].

Driver–vehicle interaction is another factor that should be taken into account as different driving styles lead to different power demands. Mathematical modeling of the vehicle and driver system can be used to analyze standardized driving cycles and different drivers behaviors [26].

These models are typically 1D models developed by handwritten equations [36,37] or dedicated physical-modeling software, such as Simscape [38], Amesim [27,39], Modelica [40] and Dymola [41–43]. The vehicle powertrain and thermal systems are modeled and a given velocity profile, either from homologation or customized cycles, is applied. Vehicle motion is reduced to the motion of a mass point. The considered vehicle components and thermal system are modeled as lumped mass models. In some cases, lookup tables can be used to reproduce the behavior of complex subsystems, such as engine and motors. Kinematic or dynamic approaches are possible [26]. In dynamic models, a driver model is also included and the driver parameters have to be carefully calibrated as they affect performances, consumption and thermal requirements. In some cases, also heat recovery systems can be included [44].

4. Thermal Management System Architectures

Given the temperature ranges of Table 1, from a conceptual point of view, four different thermal loops can be defined. Possible realizations of the loops are depicted in Figures 1–4. Combining and adapting such loops, the thermal management system of any vehicle can be obtained.

4.1. High Temperature Loop

A typical scheme of a high temperature loop is depicted in Figure 1. The high temperature loop is dedicated to the thermal management of the IC engine. In some cases, also turbocharger [45] and oil radiators [46] can be included in the loop. A proper thermal management of the engine has the following objectives [30,47,48]:

- Maintaining the IC engine in its optimal temperature range in wide range working conditions, including transient conditions [47]. Particular attention has to be paid to avoid overheating in any condition [49].
- Reduce exhaust pollutants [50].
- Reduce oil viscosity by reducing warm up time and maintaining a correct temperature [51].
- Reduce power dissipation in engine auxiliaries, such as pumps and fans [48].
- Improve combustion boundary conditions [48].

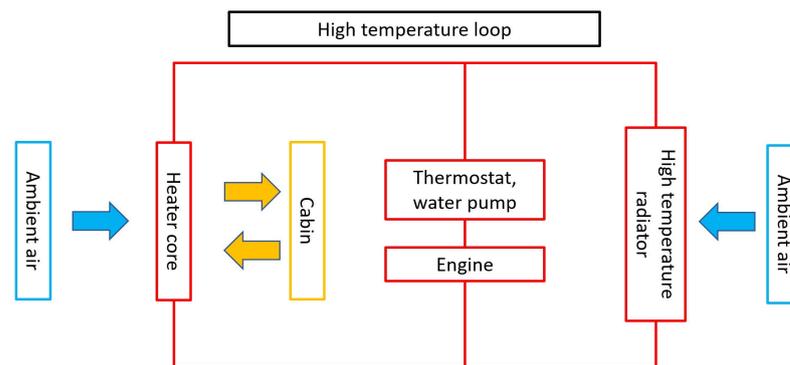


Figure 1. Scheme of a high temperature loop.

Traditionally, the cooling system of the engine is mechanically connected to the crankshaft. In this configuration, in order to avoid overheating, the system is usually over-sized [52] with negative effects on overall efficiency. Pump and fan cannot be freely controlled and the cooling system efficiency cannot be optimized in different working conditions [47].

The development of the engine cooling system is toward intelligent systems [48,53]. Fans and pumps are actuated by dedicated motors and can be controlled independently from the engine speed [54,55]. The main advantages of an intelligent engine cooling system are the following:

- Reduction of warm up time. Warm up time is of particular interest as about a third of car journeys ends before engine and lubricant oil warm up is complete [32], with 80% of US travels less than 15 km [56] and a mean travel of 10 km in Europe [57]. Homologation driving cycles also consider the warm up phase. The reduction of engine and lubrication oil warm up time has a series of beneficial consequences [47,58]:
 - Reduction of fuel consumption [59];
 - Reduction of friction losses [60].
 - Reduction of CO₂ [61];
 - Significant reduction of pollutant emissions in test cycles [62];
 - Possible reduction of NOx in Diesel engines [63];
- Reduction of heat losses, mechanical losses and parasitic losses due to high rotational speed of the engine [64].
- Optimized cooling during transient conditions. Traditional cooling systems suffer of poor regulation in most conditions [53] and in harsh environments, such as high altitude or cold climate [65]. Intelligent cooling systems can optimize the coolant flow as function of the actual condition of the vehicle.
- Reduction of radiator size [66].

The high temperature loop in general includes also a heater core to provide heat to the cabin. Such thermal transfer has the advantage of warming up the cabin with the waste heat of the engine. However, since the cabin has to be warmed up at car start up, especially in cold climates, the heat demand at the heater core can increase the warm up time [48]. This problem is particularly relevant for PHEV, where an electric cabin heater is often employed to provide the heat power demand of the cabin when the engine is cold [67].

4.2. Medium Temperature Loop

The medium temperature loop is dedicated to the cooling of the electric motors and power electronics. A scheme of a medium temperature loop is reported in Figure 2. The water pump cannot be connected to an engine, either because the vehicle is not equipped with one (EV) or the engine is often switched off (HEV and PHEV), and it is driven by a dedicated electric motor.

The radiator may exchange temperature with the cabin conditioning loop [68] or with the external environment. In most cases, due to the high efficiency of electric machines, the exchanged heat is not sufficient for cabin heating. The electric machine working temperature is of the order of 60 °C, and, in most climates, conditioned air is not needed for cooling. The medium temperature loop can exchange heat with high and/or low temperature loop. In cold weather, the wasted heat can be used to speed up the engine warm up or battery heating [23].

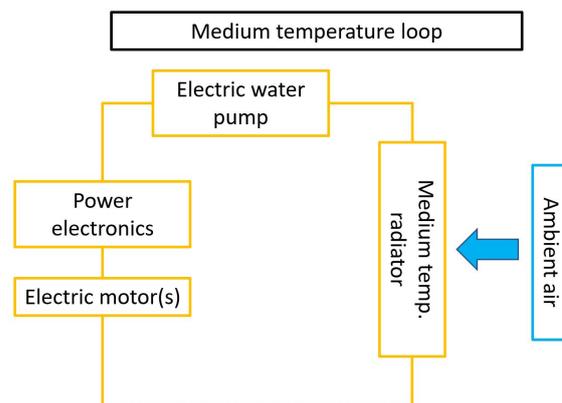


Figure 2. Scheme of a medium temperature loop.

4.3. Low Temperature Loop

The low temperature loop is in charge of the thermal management of the batteries. Depending of the vehicle configuration, mission and requirements, a large number of possible battery configurations are available. As a consequence, many different configurations of the battery thermal management loop can be found. In Figure 3, a possible configuration of a low temperature loop is depicted. In this case, a liquid cooling system is considered, however, this is not the only possibility as air cooling is also used for batteries [21]. In any case, depending on the ambient temperatures, conditioned air could be used for heat removal and a battery heater may be necessary.

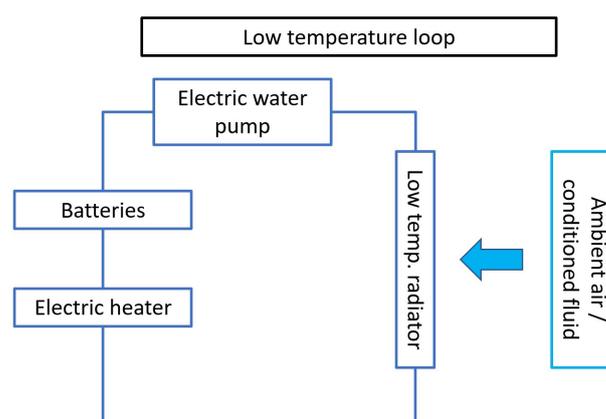


Figure 3. Scheme of a low temperature loop.

4.4. Cabin Conditioning Loop

The thermal management of the cabin is realized by an air conditioning circuit (Figure 4). If the IC engine is always available, the compressor can be connected to the engine belt. If a more flexible control of the compressor is required or the engine is not available, an electric motor can be used. Warm air can be obtained by recovering the wasted heat of the powertrain or by an electric heater. For PHEV and EV, the available

wasted heat is not sufficient for cabin warming and the electric heater is usually required. The cabin conditioning loop and the low temperature loop have very similar target temperatures, therefore, in some applications, the two loops are strictly connected and just one conditioning machine is employed [69].

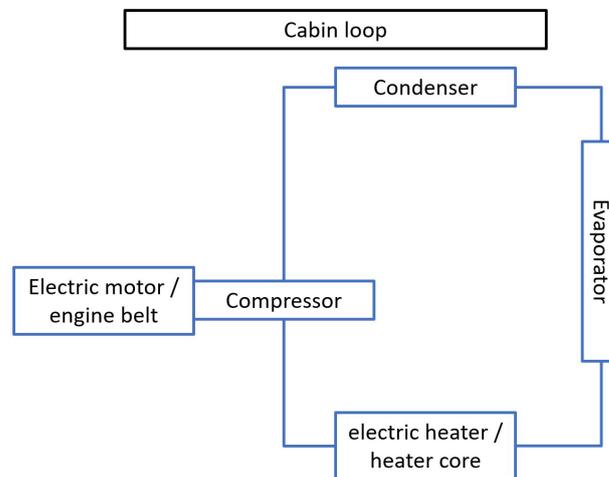


Figure 4. Scheme of a cabin conditioning loop.

4.5. Cooling Loops Modeling

The modeling of the thermal management system of vehicles is mostly realized by considering 1D physical models. Such models are able to give accurate prediction of the behavior of the system at a reasonable computational time. According to [69–71], such models can be realized at different levels of fidelity. Highly fidelity models can model complex and transient maneuvers; however, their computational cost is relatively high and cannot run in real time. Such models, although accurate, may be too slow for actual development of thermal management systems [71]. Quasi-transient models can run almost in real time at the cost of some approximations in the transient phase, while accurate results are to be expected at steady state. Faster models can be obtained by mapped models, where detailed calculations for heat exchange in different components are replaced by lookup tables or surrogate models [72–74].

In [75], an example of a mapped model of the thermal system of high voltage batteries is reported and the model is available in Matlab Simscape as built-in demo. 1D modeling of the thermal management circuits of batteries and electric motors and electronics is considered in quite a lot of papers [38,39,41,69,76–79]. In such papers, models are usually implemented by handwritten equations or by using dedicated software for physical modeling (such as Matlab Simulink and Simscape [38,69], Amesim [39], Dymola [41], Engineering Equation Solver [76,77], Modelica [78,79]). In [54,55,80–86], models of the thermal management system of IC engines are proposed with particular focus on control implementation and optimization.

To overcome the limitation of 1D models but maintaining reasonable computational time, co-simulation between 1D and 3D models has been employed [87–90]. In these models, the thermal management system is modeled by a 1D approach, while one or more key components are modeled by 3D CFD models.

5. Subsystems Description and Modeling

Beside the coolant circuits, also the thermal behavior of each component of electrified vehicles has been deeply investigated. In this section, the most important subsystems of electrified vehicles are considered.

5.1. Batteries

Batteries are probably the most currently studied subsystem. In the 2019 review paper [22], the authors list fifteen review papers dealing with battery thermal management technologies and modeling from 2004 to 2017 [15,17,19,20,91–100]. Further state-of-the-art papers have been published more recently [9,10,12,13,16,21].

Such a large research interest is motivated as batteries are the energy storage system of EV and therefore affect their performance and range. For HEV and PHEV, batteries are important as they are a key factor in the vehicle efficiency and fuel savings. Depending on the chemical composition, many different battery types are available in the market. In Figures 5 and 6, maps comparing specific energy and number of cycles and specific power and number of cycles of some battery types are shown. Specific energy is crucial for vehicle range, while specific power directly affects its performance. The number of cycles defines the expected life of the battery. Lithium-ion batteries show a great potential for vehicle applications.

5.1.1. Effects of Temperature

The values reported in Figures 5 and 6 are strongly influenced by temperature with negative effects both at low and high temperature. With particular reference to Lithium-ion batteries, different temperature-related issues have to be considered.

Referring to low temperature, the following effects on batteries have been investigated:

- *Reduction of available energy.* For temperatures below 0 °C, a significant reduction of capacity can be observed with a reduction of about 40% at −20 °C [100].
- *Increase of internal impedance.* Below −20 °C, the internal resistance of the cells is increased with a reduction of electrolyte conductivity [101,102].
- *Aging and cell degradation.* At low temperatures, the diffusion of lithium ions into graphite is reduced resulting in the lithium plating phenomenon. This leads to cell aging and severe cell degradation [103–105]. In addition, capacity fading due to loss of active material and cyclability is observed [105–108].
- *Charge time extension.* At temperature below 0 °C, the diffusivity of the lithium ions is lower in the discharged state than in the charged state. This results in more difficulties in charging a cold discharged battery than discharging a cold charged one [100,103,109,110].

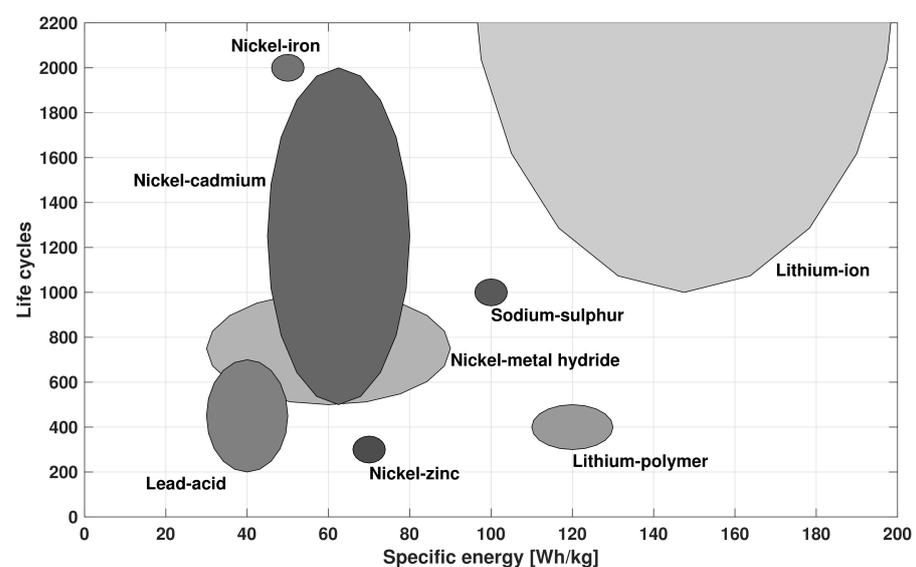


Figure 5. Battery specific energy vs. number of cycles (data adapted from [12,14,20,111–114]).

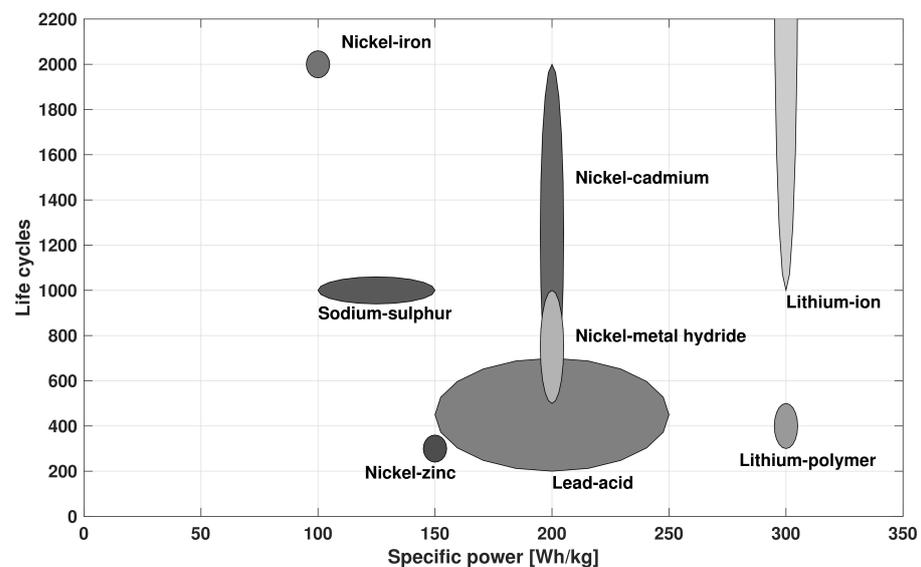


Figure 6. Battery specific power vs. number of cycles (data adapted from [12,14,20,111–114]).

High temperatures effects on batteries can be summarized as follows:

- *Capacity and power fading.* Cell capacity and power reduce as the number of cycles increases at any temperature. However, at higher temperature, this reduction is faster [115–117]. An increment in the reduction rate of a factor 2.3 has been experimentally found in [116]. This process is related to the conversion of the active material of the battery into an inactive one with subsequent increment in impedance [13].
- *Aging.* High temperature increase both calendar aging (related to battery storage periods) and cycling aging (related to battery utilization periods) of batteries [117].
- *Self discharge.* At high temperature, an increase in electronic conductivity can lead to faster self-discharge rates. This effect can be seen not only when the battery is stored at high temperature for long periods, but also for short exposure periods [22,92,118].
- *Thermal runaway.* Thermal runaway is a critical and hazardous situation in which the temperature of the battery grows over a safety threshold and undesired and uncontrollable reactions can lead to the explosion of the battery [19,20,119–122]. If the heat generated inside the battery when large amount of power is drawn is not properly removed, the temperature inside the battery can grow to dangerous temperatures (approximately 80–100 °C). Exothermic reactions happen inside the battery, increasing the temperature. Inflammable electrolytes may cause fire, smoke and even explosions. Notably, thermal runaway could also happen in parked cars at hot ambient temperatures [19].

Beside high and low temperatures, another important issue is the temperature distribution across cells and batteries [13]. Unbalanced cell temperatures aggravate the problems related to cell unbalance, leading to a more severe loss in battery capacity and increased thermal runaway risk [123]. A value of 5 °C has been indicated as uniformity interval of temperature inside the pack [124,125]. For this temperature interval, a loss of 1–2% in capacity can be expected [126].

5.1.2. Battery Thermal Management Systems

Battery thermal management has therefore the task of maintaining the battery temperature inside the working range and avoid temperature gradients. Several battery thermal management systems have been proposed. Different classifications of the thermal management systems have been proposed according to different criteria [13]. In Figure 7, a classification of the thermal management system proposed in [21] is reported. In this picture, the following three characteristics of the system are considered:

- *Power requirement.* Thermal management systems can be passive or active. A passive system utilizes only the environment, while an active system is equipped with a source for heating or cooling [127]. In [13], this criterion is restricted to the presence or absence of a vapor compression cycle.
- *Coolant medium.* The coolant medium can be air, liquid or phase changing materials (PCM). Hybrid systems combine two different media for thermal management [21].
- *Arrangement.* Arrangement refers to the way in which the coolant medium circulates. In direct approaches, the medium is directly in contact with battery cells, while in indirect systems, a thermal conductive material is interposed between medium and cells. Cell disposition and coolant flux have a strong influence on heat transfer [128]. In parallel systems, all the cells are invested by the coolant medium at the same time. This arrangement allows for a better temperature uniformity, at the cost of higher complexity [129,130].

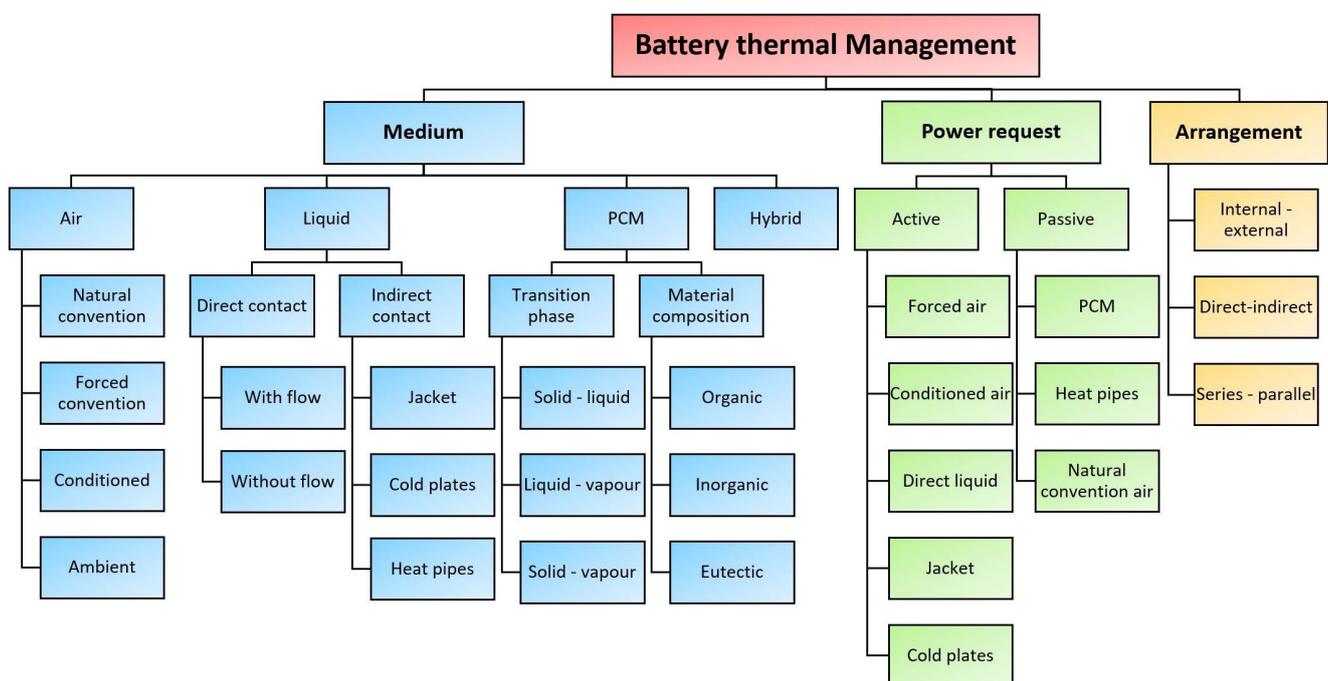


Figure 7. Classifications of battery thermal management systems (based on [21]).

Since a univocal classification is not possible, in this section, the different methods are presented mostly referring to the medium employed.

5.1.3. Air Cooling

Air cooling can be obtained in a number of configurations, including forced or natural convection and ambient or conditioned air. Three sources of air can be considered: ambient air, air from the air conditioning system and a dedicated VCC unit [13,131]. In [132], an experimental campaign has been realized to compare the effectiveness of forced or natural convection. The results show that for medium or low discharge rates, natural convection is able to control the battery temperature. However, for higher discharge rates, forced convection has to be employed. Similar results have been found in other works [133–135]. In [9,17,21], it is observed that in case of high battery size and power density and at high ambient temperatures, the demand of cooling capacities may be excessive for air thermal management systems. Ref. [18] suggests the utilization of air cooling only for HEV. However, due to its simplicity, cost effectiveness and low energy consumption, air cooling is widely diffused on the market [17]. Air thermal management can also provide hot air for battery pre-heating in cold weather [136,137].

Many research activities are in progress in air cooling battery thermal management. In [138], direct and indirect flux configurations are considered. Indirect cooling obtains higher temperature reduction with lower pressure drop, while direct cooling obtains a better uniformity. Inlet air temperature and pressure also play an important role [133,138]. Inlet and outlet geometry and cell disposition have been studied in a number of papers [11,139]. Series [124,128,140,141], parallel [55,129,142–144] and mixed series parallel [145] solutions have been proposed. In series dispositions, a temperature gradient has to be expected between the first and the last rows of cells. In parallel arrangements, a more uniform temperature distribution can be expected, however, a temperature gradient is present along the axis of the cells. In forced air, a fan is used to provide the desired flux. By optimizing the control logic of the fan, absorbed energy reduction, better uniformity and inlet pressure adjustment to the actual discharge rate can be obtained [133,146]. In [147], the use of aluminum metal foam is proposed for a better air distribution among cells.

5.1.4. Liquid Cooling

Liquid cooling systems have in general higher cooling capacities than air cooling systems. However, more complexity and safety issues have to be considered. In particular, water leakage on the cells has to be avoided. Liquid cooling can be obtained with direct or indirect contact of the heat transfer fluid with the cells. The liquid can exchange the removed heat directly with the ambient air or, for higher cooling requests, a chiller can be employed [13]. Battery heating is possible.

In direct contact systems, a dielectric liquid is circulated around the battery cells [22]. In [148–150], direct air and direct liquid (mineral and silicone oils) cooling are compared. The utilization of liquids resulted in smaller battery packs, lower energy requirements, higher cooling rate and heat transfer coefficients. The liquid heat transfer coefficient can be increased by adding nano-particles to the fluid [151–153]. A novel approach in direct contact systems is proposed in [154,155]. Battery cells are immersed in a still fluid and the heat is removed by fluid evaporation. By calibrating the boiling point of the fluid, the correct cell temperature can be maintained [156] even without a dedicated thermal control system [157].

In indirect contact systems, the liquid is not in contact with the cells but the liquid passes through a conduct, in general cold plates [158–162] or tubes [163]. The main advantage of indirect contact cooling is that also non-dielectric fluids can be used. In general, the utilized liquids, water or ethylene glycol, have a lower viscosity than oil resulting in less energy requirements from the pump [164]. If coupled with a chiller for liquid refrigeration, this system can maintain the correct battery temperature even in the worst environmental conditions with a compact design. However, due to the added complexity, there is a weight increment, maintenance issues and the risk of liquid leakage [165]. In [166], direct and indirect liquid cooling have been compared. Indirect liquid cooling, although presenting a higher thermal resistance with respect to direct liquid cooling, shows the best performance. Indirect liquid cooling could be a better solution for practical applications [167].

Heat pipes can be considered a special kind of a liquid cooling system. Heat pipes are closed pipes partially filled with a liquid. At the hot interface, the heat pipe absorbs heat and the liquid is turned into vapor. Conversely, at the cold interface, the vapor is condensed back into liquid. Heat pipes are passive devices, without any moving part, have very high thermal conductivity, homogeneous temperature distribution due to the evaporation process, very long life without maintenance requirements and flexible geometry [168]. Heat pipes can be connected to a heat and cold generation system to provide heating or cooling to the batteries [169]. Extended experimental activities have been realized for the application of heat pipes to battery thermal management [168,170–172].

5.1.5. Phase Changing Materials (PCM)

Phase change materials (PCMs) utilize the latent heat during phase changing to remove heat from batteries and are considered a very efficient battery cooling technique [12,173,174].

In particular, a passive thermal management system based on PCM feature low weight, high temperature uniformity, low energy consumption and low cost. The phase change temperature of the material is chosen according to the desired temperature of the battery. Many different materials with different phase transitions can be used. Classifications are proposed in [19,175], while in [5,175] quite complete lists of materials with phase change temperatures and latent heat are provided. In Figure 8, transition temperatures, specific latent heat and volumetric latent heat for different classes of PCM are reported. Beside transition temperature, two other properties are important for choosing the PCM when mass or dimension constraints have to be considered.

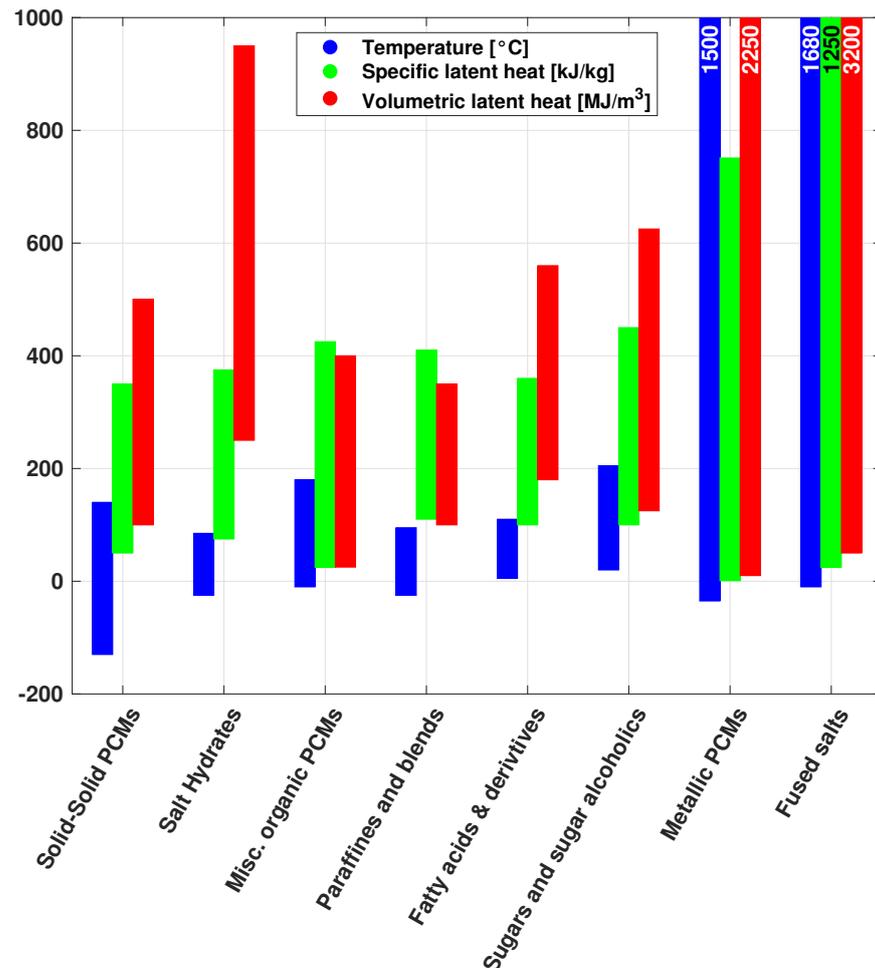


Figure 8. Transition temperature, specific latent heat and volumetric latent heat for different classes of PCM (data from [5]).

The major shortcomings of PCM are the low thermal transfer rate and low thermal capacity. Despite their inherent reliability, passive PCM systems may run out of available latent heat in hot weather or at high charging/discharging rates. To reduce the heat demand, hybrid systems can be used relaying to another medium for the peak request [21].

To increase the low thermal conductivity, nano materials with high thermal conductivity can be added to PCM [12,176–180]. In addition to increasing the contact area, they can increase the thermal conductivity. Porous media with high thermal conductivity are used [181–184]. Nano-particle additives can be used to tune the phase transition temperature and modify the thermal characteristics of the material [185].

Beside battery cooling, PCM can also be used as heat accumulators [5] in many areas of the vehicle, such as subsystems system pre-heating, passenger comfort, reduction of coolant warm up time, reduction of engine temperature oscillations and buffer between

battery cells and cooling air. By using heat accumulators, a reduction in cooling system size is envisaged. Nano-materials and nano-composites can be added to PCM to increase their thermal capacity [186].

5.1.6. Hybrid Systems

In hybrid systems, more than one of the previously described thermal management systems for the batteries are used together to improve the system mass, volume, cost and thermal performances [122,187]. Several hybrid systems combining different thermal management systems have been considered in the literature, such as natural air with forced air [188], natural air with heat pipes and spray water [189], forced air with water cooling [190,191], PCM with water cooling [192], PCM with forced air [193], PCM with heat tubes [194].

5.1.7. Battery Thermal Models

Great efforts have been devoted to the modeling of the thermal management of cells and batteries resulting in a large amount of papers discussing the topic. For battery thermal modeling, a reliable thermal model of the battery is required. Starting from the heat generated from the battery, the thermal management system can be modeled by applying the correct boundary conditions [20]. Battery thermal models are realized by considering the electrical/electrochemical characteristics and the thermal behavior of the battery [195]. Heat generation inside the batteries is governed by complex electrochemical reactions depending on temperature and state of the battery [15]. Coupled, uncoupled or partially coupled models of the battery can be realized.

Heat generation in batteries derives from reversible or irreversible losses. Reversible heat generation is due to entropy changes related to electrochemical reactions at cathode and anode. This heat can be positive or negative, therefore, its contribution is small on the whole cycle and can be neglected [196]. Irreversible losses are due to transportation resistance in solid and electrolyte phases (ohmic or joule heat), charge transfer over-potential at the solid-electrolyte interface and mass transfer limitations [197]. The internal equivalent resistance of the battery is frequency- and amplitude-dependent and it is a combination of resistance, capacity and inductance [10].

Different approaches for battery modeling can be found. Depending on the level of complexity, very different computational time and accuracy levels can be obtained [198]. The following modeling approaches are used:

- *Equivalent circuit models.* The cell is modeled by an equivalent circuit. The circuit is described in terms of basic electrical components [199,200]. The most used equivalent circuit is the RC model. The cell is modeled as a voltage source, and a series of a resistance and resistances and capacitors in parallel. The resulting model is able to predict the dissipated energy at a low computational cost and requiring few parameters to be tuned. Therefore, the model is widely employed for vehicle thermal management design at system level. Other used equivalent circuit models are PNGV (Partnership for New Generation of Vehicles) model, Rint model (Internal Resistance model) and Thevenin model [15].
- *Electrochemical models.* Electrochemical models accurately describe the chemical reactions and the charge generation in the cell [20]. In [201], the P2D (Pseudo Two-dimensional) model has been firstly presented considering a porous electrode and solution theory. The model is quite accurate, but requires a high computational time, especially if many cycles have to be simulated [202]. In order to reduce the computational time, the PP (porous electrode model with the polynomial approximation) model has been presented [203], in which the porous electrode model has a polynomial approximation. Alternatively, the SP (single particle) model in which the diffusion of the Li particles is neglected has also been presented [204]. These models have better velocity, but discrepancies have been found at high discharge rates [202].

- *Coupled thermal models.* These models couple the electrochemical models of the cell with a thermal model and are able to accurately describe the most relevant phenomena acting inside a battery cell [198]. The 3D lumped thermal mass models consider a simplified thermal model with constant temperature over the cell [15]. More accurate results can be obtained by considering local heat generation and thermal characteristics of the cell unit [205,206]. Multi-scale multi-physics models have been proposed to accurately compute the temperature distribution inside cells [207,208].

In Figure 9, the different models used for battery design are classified according to research focus, computational time and space scale (data adapted from [15,198,209,210]).

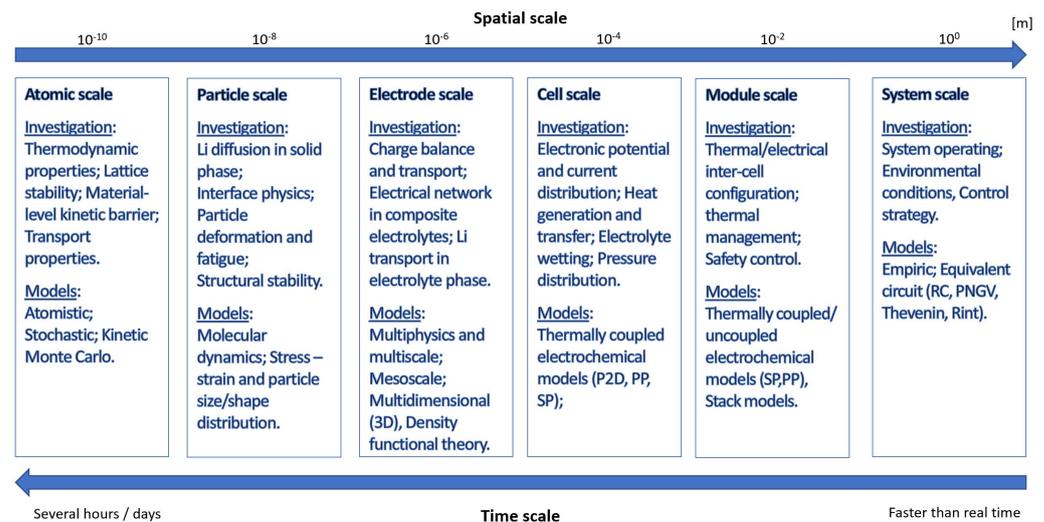


Figure 9. Types of battery models for different design focuses (adapted and data from [15,198,209,210]).

5.1.8. Battery Thermal Management System Models

Beside the thermal model of the battery, also the mathematical models of the thermal management system have been developed. Simpler models consider the thermal management system as boundary conditions for the model describing the battery. Convective and irradiation processes can be considered for direct cooling, while conduction is the prevalent mechanism when cells are in contact with a solid conductive material (indirect cooling or PCM) [20]. This approach requires a low computational time and is employed for system level simulations.

For the design of the thermal management system of the battery, detailed 3D models are employed. Several approaches can be found for the description of the battery plus thermal battery management system (see, for instance, [174] for examples). In [129], a decoupled quasi-transient lumped thermal model is employed to study the layout of a forced air battery thermal management system. CFD simulations coupled with a lumped model of single cells has been realized in [128] for the definition of the best cell arrangement of a direct parallel forced-air battery thermal management system. A similar approach has been used in [193] for the study of a hybrid cooling system with PCM and forced air. A SIMPLE (Semi-Implicit Method for Pressure Linked Equations) algorithm combined with staggered grid arrangement and central difference scheme is developed in [183] for the study of a system realized with PCM and metal foams. The heat transfer between batteries and heat pipes has been analyzed in [160] by the commercial software ANSYS Fluent. In [211], finite volume equations and a SIMPLE (Semi-Implicit Method for Pressure Linked Equations) algorithm are used to couple temperature and velocity field to simulate the thermal management of axisymmetric cylindrical Li-ion battery cells by means of PCM loaded with carbon fibers. All the considered papers focus on the development of the battery thermal management, but the models are, in general, too complex for an analysis at vehicle level.

5.2. Electric Motors

Electric motors for automotive application are characterized by high power and energy density. The current trends are toward motors with even higher power and energy density, higher efficiency, less mass, compact size and low cost [76,212]. Motor thermal management plays a crucial role in the actual performances of electric motors [213]. The classical approach in motor thermal management is based on experience starting from the motor operational conditions and by adopting large safety factors. Such an approach typically leads to over-sized and not very efficient thermal management systems [24,212,214].

Motor thermal management comprises heat generation, heat transfer from the generation point to the removal systems and heat removal. Heat generation is related to the loss inside the electric motors. In [212], six loss mechanisms are identified. Such mechanisms, in order of importance, are resistive copper losses in stator and in rotor, iron core losses, friction and windage losses and load stray losses. Heat generation can be reduced by reducing motor losses by several technological improvements, such as manufacturing of thinner laminae in rotor and stator, increase of lamination thermal conductivity and reduction of eddy currents by axial segmentation of magnets [215–217].

Heat transfer is critical to avoid heat concentration. For instance, magnetic losses are quite small, however, locally, the magnet temperature can become critical due to the long path to the heat removal system [212]. Transfer efficiency can be increased by choosing materials with high thermal conductivity for contact surfaces, thermal pastes can be used to fill voids in rotor and stator, larger contact surfaces can be used along heat transfer paths.

Different heat removal systems can be employed. In Table 2, a classification of the heat removal systems for electric motors is reported along with pertinent references. Heat can be removed at the stator core, stator winging or end winding. Depending on the location of the heat removal, different technologies can be employed [218].

Table 2. Cooling technologies for electric motors (adapted [212] and references therein).

Cooling Target	Method	References
Stator core (indirect)	Water jacket Air	[219,220]
Stator core (direct)	Water Glycol Oil	[221,222]
Stator winding	Cooling channels Filling material Heat exchanger	[223,224] [145,225] [226]
End winding	Liquid jets Spray cooling Potting material	[214,227] [228] [229,230]

The mathematical modeling of the electric motor thermal behavior can be realized by a lumped parameter thermal network (LPTN), FEA, and computational fluid dynamics (CFD) [212]. These analyses are able to predict the temperature distribution inside the motor and are suitable for motor design purposes. LPTN consists in a network of thermal nodes representing a lumped parameter description of motor components connected in a network representing the components. 2D models [231] or 3D models [232] can be obtained, depending if the axial dimension is neglected or considered. Such models can reproduce the temperature distribution inside the motor quite well, but require the identification of thermal characteristics of each component. FEM [233] and CFD models can be realized considering the actual geometry of the motor and multi-physics approaches. The coolant pipes configuration has been studied in detail [234]. Large computational times are usually required, but accurate descriptions of the temperature field can be obtained [218].

For the analysis of the thermal management at vehicle level, less computational costly models are preferred. Lookup tables tuned on experimental data or the results of complex models can be employed.

5.3. Power Electronics

Thermal management of power electronics is becoming a critical issue, especially considering the trends in miniaturization, high efficiency and compactness [24,235]. Excessive temperatures can cause failures and in general reduce the reliability of electronic components, particularly on power modules [236]. For this reason, the thermal management of power electronics is required to avoid local heat concentrations, maintain the temperature below a given value [208], provide a smooth cooling and temperature uniformity [235].

Different typologies of thermal management for power electronics are employing different media and transfer mechanisms [236]. Referring to the used medium, the following classification can be considered:

- *Solid materials.* Solid materials mostly exploit conduction for power electronics cooling. The most common and economical techniques are aluminum heat sinks [24]. The thermal transfer coefficient can be increased by utilizing advanced thermal interface materials [237]. Such materials are used to reduce the thermal resistance between contact surfaces. Polymer-based [238], carbon-based [239], thermal greases [240] and silicone gels [240] interface materials are employed.
- *Air.* Air cooling can be applied by natural or forced convection [236]. In natural convection, fins can be added to increase the convection surface. Forced air is more effective, but requires the use of fans. Synthetic and pulsating jet impingements can be used to improve the heat transfer efficiency [235,241].
- *Liquid.* Liquid cooling can be obtained by a direct immersion (with or without forced flow [242,243]) or indirectly. In the latter case, cold plates, microchannels, electrowetting or jet impingement can be used [236,244]. In some cases, these methods can be used with two-phase materials. Two-phase materials can be also used in heat pipes and spray cooling [245].
- *Phase changing materials.* PCM have a significant potential for electronic cooling due to the high energy storage of the latent heat and constant temperature during the transformation. For electronic components cooling, organic PCM are mostly used for their lower cost and good properties [246]. However, due to the low thermal conductivity, thermal conductivity enhancers, such as nanoparticles [247] or fins [248], are usually employed.

Cutting edge technologies, such as magnetic cooling, thermoelectric cooling, thermotunneling and thermoionic cooling, are also applied [236].

For the modeling of power electronic cooling, conduction, convection and fluid distribution around components should be investigated with respect to the actual geometry. For such an analysis, CFD is a powerful tool able to compute the temperature distribution [249,250]. However, due to the complexity of the problem, this method has high computational time and, sometimes, convergence problems [251]. A different approach is the flow network modeling (FNM) which consists in lumped parameter models of the system [251–253]. This method is much faster than CFD, however, the thermal coefficients are usually known only for standard components. Hybrid approaches using CFD for the definition of the coefficients used in the FNM model can be found [254].

5.4. Under Hood

For HEV and PHEV, under-hood heat retention is important for maintaining engine and fluid temperature and mitigating the problems related to engines operating at low temperatures (see Section 4.1). Beneficial effects can be seen both in the homologation cycles and in real-world vehicle utilization. In fact, the Ambient Temperature Correction Test contains two World-wide harmonized Light duty Test Procedure (WLTP) cycles at different ambient temperatures separated by 9 h [255]. In real world utilization, vehicles

are generally used for short distances [56,57] and HEV and especially PHEV have periods of travel with the engine switched off. Thermal encapsulations of the powertrain has the potential to improve fuel consumption and emissions in applications with frequent cold starts [256–258].

Modeling of under-hood heat retention is a particularly complex problem [26]. Complex dynamic CFD models have to be realized of the soak period considering the geometry of the under-hood components, convection, conduction and radiation. Particularly challenging is the computation of thermally induced convective heat transfer due to buoyancy [26,258–260]. Such models are computationally costly and a trade-off has to be found between computational time and accuracy. In [261], a 3D model is employed to provide the boundary conditions to a 1D model.

For EV, under-hood analyses are important to understand the interaction between different vehicle subsystems located in the same enclosed environment. In [262], a 1D/3D coupled model is realized in order to understand the interaction between powertrain and air conditioning systems and their impact on the vehicle thermal management system.

5.5. Cabin

Cabin Heating, Ventilation and Air Conditioning (HVAC) system has the task to provide a comfortable environment to the occupants of the vehicle. Air quality is also important as the content of CO₂ can increase accident risk [263,264]. Cabin temperature and humidity depend on many factors, namely heat transfer from the ambient through car body and windows (convection and radiation), body heat and humidity from occupants, heat from car subsystems and air from the HVAC system. The thermal management of the cabin requires a sensible amount of energy and, for EV, an efficient system is critical for vehicle autonomy. According to [265,266], up to 50% range reduction can be observed in cold weather. In fact, EV vehicle drive systems have a very high efficiency, therefore, the amount of wasted heat is not sufficient for cabin warming and a heater is necessary [68].

Positive Temperature Coefficient (PTC) heaters with capacities between 5 kW and 10 kW [267] are usually employed as cabin heaters in electrified vehicles. Such power is similar to the mean power request during an NDC cycle which ranges from 3 kW for compact cars to 7 kW for large SUVs [268,269]. To reduce power consumption in mild cold temperatures, above -10 °C, heat pumps can be utilized [270]. The author of [271] has shown that heat pumps could also be used at temperatures as low as -30 °C. As a result, beside the use of a PTC alone, HVAC configurations with smaller PTC plus heat pumps are used. In some cases, an internal heat recovery from the vehicle powertrain or electric components can also be added [68,272].

Thermal modeling of the cabin is complicated by the complex geometry of the interior that should be considered and the number of heat and humidity sources and sinks. Several approaches have been developed depending on the target of the simulation. For the design of the HVAC systems, high-fidelity numerical simulations considering all of the involved phenomena realized by CFD software are employed [263,273,274]. Such models require a long computational time. To reduce the impact of the computational time, 1D/3D models and surrogate models can be realized [275,276].

For system design, lumped parameters models or 1D physical models are developed with dedicated software or handwritten equations [277–280]. Such models can consider static and transient analyses [26].

6. Thermal Management System Optimization

From a system engineering perspective, the optimization of the thermal management system should be performed at vehicle level considering the behavior of all subsystems. However, due to the complexity of the system and computational difficulties, such an approach is seldom realized. Often, the optimization is performed by considering a single subsystem. This approach tends to give a partial view of the system and integration problems can arise when the full vehicle is considered [26]. In general, if the optimization

is focused on a single subsystem, the mutual effects of changing its design on the whole system and of the changes of system on its performances are neglected. As a consequence, when integrating the different subsystems, the resulting system composed by singularly optimized subsystems is not the optimal solution at system level [269,281].

Due to their importance, in several papers, the optimization of the thermal management system of batteries is discussed. Its optimization is performed by means of multi-disciplinary optimization approaches. In [282], a mono-objective optimization of a PCM battery cooling system is presented for mass minimization with a constraint on the temperature distribution in the battery. Genetic algorithms are used in [283] for the maximization of the Nusselt number in a forced air cooling system. Multi-objective optimization is also considered. In [284–286], multi-objective optimizations by means of multi-physics models of battery thermal management systems are discussed. In these cases, very complex CFD and FEM models are developed and validated. As the resulting models require large computational times, surrogate models are used to speed up the computational time. In all the considered cases, the thermal management system of the vehicle is not considered in the analysis.

System level optimization is also considered. In these cases, different strategies can be adopted. In [76], a Pareto-Optimal optimization is performed considering a 1D lumped parameter model of the system. Design parameters pertaining to different subsystems are used to optimize the global performance of the system. In [287], the thermal management system is modeled by a 1D CFD approach where radiators and cabin have been modeled with a full 3D CFD. This model has been used to optimize the thermal parameters of the cabin model to match experimental data. 1D/3D co-simulation techniques are becoming more and more important for realizing a simulation framework able to provide accurate and fast models for system optimization [26,27].

Special attention has to be devoted to the design and optimization of the thermal management control. In [288], the optimization of HEVs is deeply analyzed. It is pointed out that to obtain the best performances from the vehicle system, thermal management system and control must be optimized at the same time. However, due to the multi-disciplinarity and complexity of the system, special strategies have to be implemented for the optimization process. Referring to the theory of coupled plant and control optimization [289], it is firstly remarked that although such approaches give a sub-optimal solution, they provide a deep insight into the problem. For the control and thermal management system (plant) optimization, four strategies are possible, namely design the plant first, then the control, alternating plant and control optimization, control design nested within the plant design and simultaneous control and plant optimization. The first approach is the simplest but less effective, as it consists of first designing the thermal management system and then implementing the optimal control without any interaction with the system design.

7. Conclusions

In this paper, the main aspects of the thermal management of electrified vehicles have been analyzed from a system engineering perspective. The review has covered the fundamental aspects for the design and optimization of the thermal management system in a multi-disciplinary framework. In the current trend of increasing performances, reliability, power and energy, the system engineer has to be familiar with the many modeling issues involved in the design of electrified vehicles and in particular of their thermal management.

Firstly, mission and ambient have been considered and related to the requirements on the thermal management. At system level, the vision of the desired utilization of the vehicle defines targets and constraints of the subsequent design. The mathematical tools referring to the analysis of vehicle performances and interactions with driver and ambient have been discussed.

The basic architectures of the thermal management circuits for the main subsystems of electrified vehicles have been presented, considering their functions, requirements and interactions with reference to engineering solutions and mathematical models.

The thermal managing of each subsystem of the vehicle has its own requirements and constraints. Batteries have been deeply discussed as they are the most critical subsystem. However, issues and opportunities referring to motors, power electronics, under hood soaking and cabin conditioning have been analyzed. The detailed mathematical modeling of such subsystems is very complex and requires large computational time, as many physical and thermodynamics phenomena are involved. Models have to be tailored for the desired type of analysis, surrogate or lumped parameters models have to be employed for system level analyses. Co-simulation strategies could be investigated to reduce the computational time and make more complex models manageable for system optimization.

Finally, the optimization of the thermal management system has been discussed. For the optimization of such a complex system, computational time and power is still an issue. Techniques are available to realize a system level optimization, but developments in computational models and co-simulation techniques are still required.

Proper thermal management design and optimization has proved to increase vehicle performances and range. The study of the literature has clearly shown that thermal managements is a complex and multidisciplinary problem. Several phenomena have to be modeled requiring dedicated optimization procedures at system level still to be developed.

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References

1. European Commission (EC). *EU Transport in Figures STATISTICAL Pocketbook 2020*; EC: Luxembourg, 2020.
2. U.S. Environmental Protection Agency (EPA). *U.S. Transportation Sector Greenhouse Gas Emissions 1990–2019*; EPA: Washington, DC, USA, 2021.
3. Canals Casals, L.; Martinez-Laserna, E.; Amante García, B.; Nieto, N. Sustainability analysis of the electric vehicle use in Europe for CO₂ emissions reduction. *J. Clean. Prod.* **2016**, *127*, 425–437. [[CrossRef](#)]
4. Wei, C.; Hofman, T.; Caarls, E.I.; Van Iperen, R. A review of the integrated design and control of electrified vehicles. *Energies* **2020**, *13*, 1–31. [[CrossRef](#)]
5. Jankowski, N.R.; McCluskey, F.P. A review of phase change materials for vehicle component thermal buffering. *Appl. Energy* **2014**, *113*, 1525–1561. [[CrossRef](#)]
6. Liu, Y.; Canova, M.; Wang, Y.Y. Distributed energy and thermal management of a 48-V diesel mild hybrid electric vehicle with electrically heated catalyst. *IEEE Trans. Control Syst. Technol.* **2020**, *28*, 1878–1891. [[CrossRef](#)]
7. Popescu, M.; Staton, D.A.; Boglietti, A.; Cavagnino, A.; Hawkins, D.; Goss, J. Modern Heat Extraction Systems for Power Traction Machines—A Review. *IEEE Trans. Ind. Appl.* **2016**, *52*, 2167–2175. [[CrossRef](#)]
8. Iradukunda, A.C.; Huitink, D.R.; Luo, F. A review of advanced thermal management solutions and the implications for integration in high-voltage packages. *IEEE J. Emerg. Sel. Top. Power Electron.* **2020**, *8*, 256–271. [[CrossRef](#)]
9. Kumar, P.; Chaudhary, D.; Varshney, P.; Varshney, U.; Yahya, S.M.; Rafat, Y. Critical review on battery thermal management and role of nanomaterial in heat transfer enhancement for electrical vehicle application. *J. Energy Storage* **2020**, *32*, 102003. [[CrossRef](#)]
10. Choudhari, V.G.; Dhoble, D.A.; Sathe, T.M. A review on effect of heat generation and various thermal management systems for lithium ion battery used for electric vehicle. *J. Energy Storage* **2020**, *32*, 101729. [[CrossRef](#)]
11. Xia, G.; Cao, L.; Bi, G. A review on battery thermal management in electric vehicle application. *J. Power Sources* **2017**, *367*, 90–105. [[CrossRef](#)]
12. Shen, Z.G.; Chen, S.; Liu, X.; Chen, B. A review on thermal management performance enhancement of phase change materials for vehicle lithium-ion batteries. *Renew. Sustain. Energy Rev.* **2021**, *148*, 111301. [[CrossRef](#)]
13. Kim, J.; Oh, J.; Lee, H. Review on battery thermal management system for electric vehicles. *Appl. Therm. Eng.* **2019**, *149*, 192–212. [[CrossRef](#)]

14. Al-Zareer, M.; Dincer, I.; Rosen, M.A. A review of novel thermal management systems for batteries. *Int. J. Energy Res.* **2018**, *42*, 3182–3205. [[CrossRef](#)]
15. Wang, Q.; Jiang, B.; Li, B.; Yan, Y. A critical review of thermal management models and solutions of lithium-ion batteries for the development of pure electric vehicles. *Renew. Sustain. Energy Rev.* **2016**, *64*, 106–128. [[CrossRef](#)]
16. Siddique, A.R.M.; Mahmud, S.; Heyst, B.V. A comprehensive review on a passive (phase change materials) and an active (thermoelectric cooler) battery thermal management system and their limitations. *J. Power Sources* **2018**, *401*, 224–237. [[CrossRef](#)]
17. An, Z.; Jia, L.; Ding, Y.; Dang, C.; Li, X. A review on lithium-ion power battery thermal management technologies and thermal safety. *J. Therm. Sci.* **2017**, *26*, 391–412. [[CrossRef](#)]
18. Khan, M.R.; Swierczynski, M.J.; Kær, S.K. Towards an ultimate battery thermal management system: A review. *Batteries* **2017**, *3*, 9. [[CrossRef](#)]
19. Malik, M.; Dincer, I.; Rosen, M.A. Review on use of phase change materials in battery thermal management for electric and hybrid electric vehicles. *Int. J. Energy Res.* **2016**, *40*, 1011–1031. [[CrossRef](#)]
20. Liu, H.; Wei, Z.; He, W.; Zhao, J. Thermal issues about Li-ion batteries and recent progress in battery thermal management systems: A review. *Energy Convers. Manag.* **2017**, *150*, 304–330. [[CrossRef](#)]
21. Kannan, C.; Vignesh, R.; Karthick, C.; Ashok, B. Critical review towards thermal management systems of lithium-ion batteries in electric vehicle with its electronic control unit and assessment tools. *Proc. Inst. Mech. Eng. Part D J. Automob. Eng.* **2021**, *235*, 1783–1807. [[CrossRef](#)]
22. Wu, W.; Wang, S.; Wu, W.; Chen, K.; Hong, S.; Lai, Y. A critical review of battery thermal performance and liquid based battery thermal management. *Energy Convers. Manag.* **2019**, *182*, 262–281. [[CrossRef](#)]
23. Zhang, T.; Gao, C.; Gao, Q.; Wang, G.; Liu, M.H.; Guo, Y.; Xiao, C.; Yan, Y.Y. Status and development of electric vehicle integrated thermal management from BTM to HVAC. *Appl. Therm. Eng.* **2015**, *88*, 398–409. [[CrossRef](#)]
24. Lajunen, A.; Yang, Y.; Emadi, A. Recent Developments in Thermal Management of Electrified Powertrains. *IEEE Trans. Veh. Technol.* **2018**, *67*, 11486–11499. [[CrossRef](#)]
25. Li, Z.; Khajepour, A.; Song, J. A comprehensive review of the key technologies for pure electric vehicles. *Energy* **2019**, *182*, 824–839. [[CrossRef](#)]
26. Yuan, R.; Fletcher, T.; Ahmedov, A.; Kalantzis, N.; Pezouvanis, A.; Dutta, N.; Watson, A.; Ebrahimi, K. Modelling and Co-simulation of hybrid vehicles: A thermal management perspective. *Appl. Therm. Eng.* **2020**, *180*, 115883. [[CrossRef](#)]
27. Wang, Y.; Gao, Q.; Zhang, T.; Wang, G.; Jiang, Z.; Li, Y. Advances in integrated vehicle thermal management and numerical simulation. *Energies* **2017**, *10*, 1636. [[CrossRef](#)]
28. Deng, T.; Ran, Y.; Yin, Y.; Liu, P. Multi-objective optimization design of thermal management system for lithium-ion battery pack based on Non-dominated Sorting Genetic Algorithm II. *Appl. Therm. Eng.* **2020**, *164*, 114394. [[CrossRef](#)]
29. Bulut, E.; Albak, E.; Sevilgen, G.; Ozturk, F. A new approach for battery thermal management system design based on Grey Relational Analysis and Latin Hypercube Sampling. *Case Stud. Therm. Eng.* **2021**, *28*, 1–17. [[CrossRef](#)]
30. Moller, D.; Aurich, J.; Mehnert, R. Higher Cruising Range Through Smart Thermal Management in Electric Vehicles—Interaction Between Air Conditioning and Cooling System Components in the Overall Network. In *Energy and Thermal Management, Air-Conditioning, and Waste Heat Utilization*; Junior, C., Dingel, O., Eds.; Springer International Publishing: Cham, Switzerland, 2019; pp. 15–29.
31. Karabasoglu, O.; Michalek, J. Influence of driving patterns on life cycle cost and emissions of hybrid and plug-in electric vehicle powertrains. *Energy Policy* **2013**, *60*, 445–461. [[CrossRef](#)]
32. André, M. In Actual Use Car Testing: 70,000 Kilometers and 10,000 Trips by 55 French Cars under Real Conditions. *SAE Trans.* **1991**, *100*, 1–12. [[CrossRef](#)]
33. Whitefoot, J.W.; Ahn, K.; Papalambros, P.Y. The Case for Urban Vehicles: Powertrain Optimization of a Power-Split Hybrid for Fuel Economy on Multiple Drive Cycles. In Proceedings of the ASME International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, Montreal, QC, Canada, 15–18 August 2010; Volume 4, pp. 197–204. [[CrossRef](#)]
34. Patil, R.; Adornato, B.; Filipi, Z. Design optimization of a series plug-in hybrid electric vehicle for real-world driving conditions. *SAE Tech. Pap.* **2010**, *3*, 655–665. [[CrossRef](#)]
35. Battery Safety Standards Committee. *SAE J2929—Safety Standard for Electric and Hybrid Vehicle Propulsion Battery Systems Utilizing Lithium-based Rechargeable Cells*; Society of Automotive Engineers International: Warrendale, PA, USA, 2013.
36. Musardo, C.; Rizzoni, G.; Guezennec, Y.; Staccia, B. A-ECMS: An adaptive algorithm for hybrid electric vehicle energy management. *Eur. J. Control* **2005**, *11*, 509–524. [[CrossRef](#)]
37. Nüesch, T.; Cerofolini, A.; Mancini, G.; Cavina, N.; Onder, C.; Guzzella, L. Equivalent Consumption Minimization Strategy for the Control of Real Driving NOx Emissions of a Diesel Hybrid Electric Vehicle. *Energies* **2014**, *7*, 3148–3178. [[CrossRef](#)]
38. Carroll, J.K.; Alzorgan, M.; Page, C.; Mayyas, A.R. Active Battery Thermal Management within Electric and Plug-In Hybrid Electric Vehicles. *SAE Tech. Pap.* **2016**. [[CrossRef](#)]
39. Shen, M.; Gao, Q. System simulation on refrigerant-based battery thermal management technology for electric vehicles. *Energy Convers. Manag.* **2020**, *203*, 112176. [[CrossRef](#)]
40. Bouvy, C.; Baltzer, S.; Jeck, P.; Gissing, J.; Lichius, T.; Eckstein, L. Holistic vehicle simulation using Modelica—An application on thermal management and operation strategy for electrified vehicles. In Proceedings of the 9th International MODELICA Conference, Munich, Germany, 3–5 September 2012; Volume 76, pp. 264–270. [[CrossRef](#)]

41. Shet, V.V.; Ponangi, B.R.; Jacob, K. Design of a thermal management system for a battery pack in an electric vehicle using Dymola. *Heat Transf.* **2020**, *49*, 2686–2705. [[CrossRef](#)]
42. Picarelli, A.; Avila, V.; Robinson, S.P. Thermal management strategies for integrated hybrid vehicle subsystems. *IET Conf. Publ.* **2016**, *2016*, 1–6. [[CrossRef](#)]
43. Cheng, C.; McGordon, A.; Jones, R.P.; Jennings, P.A. Development of a comprehensive and flexible forward dynamic powertrain simulation tool for various hybrid electric vehicle architectures. *Proc. Inst. Mech. Eng. Part D J. Automob. Eng.* **2012**, *226*, 385–398. [[CrossRef](#)]
44. Tian, Z.; Gu, B.; Gao, W.; Zhang, Y. Performance evaluation of an electric vehicle thermal management system with waste heat recovery. *Appl. Therm. Eng.* **2020**, *169*, 114976. [[CrossRef](#)]
45. Mirajkar, N.S.; Adhikarath Tharayi, R. Thermal management in engine compartment for efficient working of the intercooler on a rear engine vehicle. *SAE Tech. Pap.* **2012**. [[CrossRef](#)]
46. Burke, R.D.; Brace, C.J.; Hawley, J.G.; Pegg, I. Review of the systems analysis of interactions between the thermal, lubricant, and combustion processes of diesel engines. *Proc. Inst. Mech. Eng. Part D J. Automob. Eng.* **2010**, *224*, 681–704. [[CrossRef](#)]
47. Liu, H.; Wen, M.; Yang, H.; Yue, Z.; Yao, M. A Review of Thermal Management System and Control Strategy for Automotive Engines. *J. Energy Eng.* **2021**, *147*, 03121001. [[CrossRef](#)]
48. Pang, H.H.; Brace, C.J. Review of engine cooling technologies for modern engines. *Proc. Inst. Mech. Eng. Part D J. Automob. Eng.* **2004**, *218*, 1209–1215. [[CrossRef](#)]
49. Wagner, J.R.; Srinivasan, V.; Dawson, D.M.; Marotta, E.E. Smart thermostat and coolant pump control for engine thermal management systems. *SAE Tech. Pap.* **2003**. [[CrossRef](#)]
50. Yao, B.; Yang, F.; Zhang, H.; Wang, E.; Yang, K. Analyzing the performance of a dual loop organic rankine cycle system for waste heat recovery of a heavy-duty compressed natural gas engine. *Energies* **2014**, *7*, 7794–7815. [[CrossRef](#)]
51. Di Battista, D.; Cipollone, R. Experimental and numerical assessment of methods to reduce warm up time of engine lubricant oil. *Appl. Energy* **2016**, *162*, 570–580. [[CrossRef](#)]
52. Wang, T.; Wagner, J. Advanced automotive thermal management—Nonlinear radiator fan matrix control. *Control Eng. Pract.* **2015**, *41*, 113–123. [[CrossRef](#)]
53. Brace, C.J.; Burnham-Slipper, H.; Wijetunge, R.S.; Vaughan, N.D.; Wright, K.; Blight, D. Integrated cooling systems for passenger vehicles. *SAE Tech. Pap.* **2001**. [[CrossRef](#)]
54. Salah, M.H.; Mitchell, T.H.; Wagner, J.R.; Dawson, D.M. Nonlinear-control strategy for advanced vehicle thermal-management systems. *IEEE Trans. Veh. Technol.* **2008**, *57*, 127–137. [[CrossRef](#)]
55. Wang, T.; Tseng, K.J.; Zhao, J. Development of efficient air-cooling strategies for lithium-ion battery module based on empirical heat source model. *Appl. Therm. Eng.* **2015**, *90*, 521–529. [[CrossRef](#)]
56. Goettler, H.J.; Vidger, L.J.; Majkrzak, D.S. The Effect of Exhaust-to-Coolant Heat Transfer on Warm-up Time and Fuel Consumption of Two Automobile Engines. *SAE Tech. Pap.* **1986**. [[CrossRef](#)]
57. Jarrier, L.; Champoussin, J.C.; Yu, R.; Gentile, D. Warm-up of a D.I. diesel engine: Experiment and modeling. *SAE Tech. Pap.* **2000**. [[CrossRef](#)]
58. Roberts, A.; Brooks, R.; Shipway, P. Internal combustion engine cold-start efficiency: A review of the problem, causes and potential solutions. *Energy Convers. Manag.* **2014**, *82*, 327–350. [[CrossRef](#)]
59. Chiara, F.; Canova, M. A review of energy consumption, management, and recovery in automotive systems, with considerations of future trends. *Proc. Inst. Mech. Eng. Part D J. Automob. Eng.* **2013**, *227*, 914–936. [[CrossRef](#)]
60. Zammit, J.P.; Shayler, P.; Pegg, I. Thermal coupling and energy flows between coolant, engine structure and lubricating oil during engine warm up. In *Proceedings of the Vehicle Thermal Management Systems Conference and Exhibition (VTMS10)*; Elsevier: Amsterdam, The Netherlands, 2011; pp. 177–188. [[CrossRef](#)]
61. Dardiotis, C.; Martini, G.; Marotta, A.; Manfredi, U. Low-temperature cold-start gaseous emissions of late technology passenger cars. *Appl. Energy* **2013**, *111*, 468–478. [[CrossRef](#)]
62. Will, F.; Boretti, A. A New Method to Warm Up Lubricating Oil to Improve the Fuel Efficiency During Cold Start. *SAE Int. J. Engines* **2011**, *4*, 175–187. [[CrossRef](#)]
63. Pang, H.H.; Brace, C.J.; Akehurst, S. Potential of a controllable engine cooling system to reduce NOx emissions in diesel engines. *SAE Tech. Pap.* **2004**. [[CrossRef](#)]
64. Mohamed, E.S. Development and analysis of a variable position thermostat for smart cooling system of a light duty diesel vehicles and engine emissions assessment during NEDC. *Appl. Therm. Eng.* **2016**, *99*, 358–372. [[CrossRef](#)]
65. He, C.; Ge, Y.; Ma, C.; Tan, J.; Liu, Z.; Wang, C.; Yu, L.; Ding, Y. Emission characteristics of a heavy-duty diesel engine at simulated high altitudes. *Sci. Total Environ.* **2011**, *409*, 3138–3143. [[CrossRef](#)]
66. Cho, H.; Jung, D.; Filipi, Z.S.; Assanis, D.N.; Vanderslice, J.; Bryzik, W. Application of controllable electric coolant pump for fuel economy and cooling performance improvement. *J. Eng. Gas Turbines Power* **2007**, *129*, 239–244. [[CrossRef](#)]
67. Shams-Zahraei, M.; Kouzani, A.Z.; Kutter, S.; Bäker, B. Integrated thermal and energy management of plug-in hybrid electric vehicles. *J. Power Sources* **2012**, *216*, 237–248. [[CrossRef](#)]
68. Lajunen, A. Energy Efficiency and Performance of Cabin Thermal Management in Electric Vehicles. *SAE Tech. Pap.* **2017**, 2017. [[CrossRef](#)]

69. Kiss, T.; Lustbader, J.; Leighton, D. Modeling of an Electric Vehicle Thermal Management System in MATLAB/Simulink. *SAE Tech. Pap.* **2015**, *2015*, 21–23. [[CrossRef](#)]
70. Kiss, T.; Chaney, L.; Meyer, J. New automotive air conditioning system simulation tool developed in MATLAB/simulink. *SAE Int. J. Passeng. Cars-Mech. Syst.* **2013**, *6*, 826–840. [[CrossRef](#)]
71. Kiss, T.; Lustbader, J. Comparison of the Accuracy and Speed of Transient Mobile A/C System Simulation Models. *SAE Int. J. Passeng. Cars-Mech. Syst.* **2014**, *7*, 739–754. [[CrossRef](#)]
72. He, Y.; Lin, C.C. Development and validation of a mean value engine model for integrated engine and control system simulation. *SAE Tech. Pap.* **2007**, *2007*, 776–790. [[CrossRef](#)]
73. Isermann, R.; Automation, P. Modeling and Adaptive Control of Combustion Engines with Fast Neural Networks Identification of Nonlinear Systems: Look-Up Tables. *Learning* **2001**, *13*, 15.
74. Canova, M.; Fiorani, P.; Gambarotta, A.; Tonetti, M. A real-time model of a small turbocharged Multijet Diesel engine: Application and validation. *SAE Tech. Pap.* **2005**, *2005*. [[CrossRef](#)]
75. Huria, T.; Ceraolo, M.; Gazzarri, J.; Jackey, R. High fidelity electrical model with thermal dependence for characterization and simulation of high power lithium battery cells. In Proceedings of the 2012 IEEE International Electric Vehicle Conference (IEVC 2012), Greenville, SC, USA, 4–8 March 2012. [[CrossRef](#)]
76. Hamut, H.S.; Dincer, I.; Naterer, G.F. Analysis and optimization of hybrid electric vehicle thermal management systems. *J. Power Sources* **2014**, *247*, 643–654. [[CrossRef](#)]
77. Hamut, H.S.; Dincer, I.; Naterer, G.F. Exergoenvironmental analysis of hybrid electric vehicle thermal management systems. *J. Clean. Prod.* **2014**, *67*, 187–196. [[CrossRef](#)]
78. Austin, K.; Botte, V. An integrated air conditioning (AC) circuit and cooling circuit simulation model. *SAE Tech. Pap.* **2001**. [[CrossRef](#)]
79. Limperich, D.; Braun, M.; Pröllß, K. System simulation of automotive refrigeration cycles. In Proceedings of the Fourth International Modelica Conference, Hamburg-Harburg, Germany, 7–8 March 2005; pp. 193–199.
80. Salah, M.H.; Mitchell, T.H.; Wagner, J.R.; Dawson, D.M. A smart multiple-loop automotive cooling system-model, control, and experimental study. *IEEE/ASME Trans. Mechatron.* **2010**, *15*, 117–124. [[CrossRef](#)]
81. Zhou, B.; Lan, X.D.; Xu, X.H.; Liang, X.G. Numerical model and control strategies for the advanced thermal management system of diesel engine. *Appl. Therm. Eng.* **2015**, *82*, 368–379. [[CrossRef](#)]
82. Cipollone, R.; Di Battista, D.; Gualtieri, A. A novel engine cooling system with two circuits operating at different temperatures. *Energy Convers. Manag.* **2013**, *75*, 581–592. [[CrossRef](#)]
83. Banjac, T.; Wurzenberger, J.C.; Katrašnik, T. Assessment of engine thermal management through advanced system engineering modeling. *Adv. Eng. Softw.* **2014**, *71*, 19–33. [[CrossRef](#)]
84. Caresana, F.; Bilancia, M.; Bartolini, C.M. Numerical method for assessing the potential of smart engine thermal management: Application to a medium-upper segment passenger car. *Appl. Therm. Eng.* **2011**, *31*, 3559–3568. [[CrossRef](#)]
85. Menken, J.C.; Koerner, J.E.; Weustenfeld, T.A.; Strasser, K.; Koehler, J. Simulative comparison of conventional and secondary loop automotive refrigeration systems. In Proceedings of the Vehicle Thermal Management Systems Conference, VTMS 2015, Nottingham, UK, 10–13 May 2015; Volume 2015, pp. 511–523.
86. Kang, H.; Ahn, H.; Min, K. Smart cooling system of the double loop coolant structure with engine thermal management modeling. *Appl. Therm. Eng.* **2015**, *79*, 124–131. [[CrossRef](#)]
87. Lu, P.; Gao, Q.; Wang, Y. The simulation methods based on 1D/3D collaborative computing for the vehicle integrated thermal management. *Appl. Therm. Eng.* **2016**, *104*, 42–53. [[CrossRef](#)]
88. Fletcher, T.; Kalantzis, N.; Ahmedov, A.; Yuan, R.; Ebrahimi, K.; Dutta, N.; Price, C. Holistic Thermal Energy Modelling for Full Hybrid Electric Vehicles (HEVs). *SAE Tech. Pap.* **2020**, *2020*, 1–15. [[CrossRef](#)]
89. Kumar, V.; Shendge, S.A.; Baskar, S. Underhood thermal simulation of a small passenger vehicle with rear engine compartment to evaluate and enhance radiator performance. *SAE Tech. Pap.* **2010**. [[CrossRef](#)]
90. Watanabe, N.; Kubo, M.; Yomoda, N. An 1D-3D Integrating Numerical Simulation for Engine Cooling Problem. *SAE Tech. Pap.* **2006**. [[CrossRef](#)]
91. Cosley, M.R.; Garcia, M.P. Battery thermal management system. In Proceedings of the INTELEC, International Telecommunications Energy Conference (Proceedings), Chicago, IL, USA, 19–23 September 2004; pp. 38–45.
92. Bandhauer, T.M.; Garimella, S.; Fuller, T.F. A Critical Review of Thermal Issues in Lithium-Ion Batteries. *J. Electrochem. Soc.* **2011**, *158*, R1. [[CrossRef](#)]
93. Rao, Z.; Wang, S. A review of power battery thermal energy management. *Renew. Sustain. Energy Rev.* **2011**, *15*, 4554–4571. [[CrossRef](#)]
94. Xu, X.M.; He, R. Review on the heat dissipation performance of battery pack with different structures and operation conditions. *Renew. Sustain. Energy Rev.* **2014**, *29*, 301–315. [[CrossRef](#)]
95. Ling, Z.; Zhang, Z.; Shi, G.; Fang, X.; Wang, L.; Gao, X.; Fang, Y.; Xu, T.; Wang, S.; Liu, X. Review on thermal management systems using phase change materials for electronic components, Li-ion batteries and photovoltaic modules. *Renew. Sustain. Energy Rev.* **2014**, *31*, 427–438. [[CrossRef](#)]
96. Zhao, R.; Zhang, S.; Liu, J.; Gu, J. A review of thermal performance improving methods of lithium ion battery: Electrode modification and thermal management system. *J. Power Sources* **2015**, *299*, 557–577. [[CrossRef](#)]

97. Shabani, B.; Biju, M. Theoretical modelling methods for thermal management of batteries. *Energies* **2015**, *8*, 10153–10177. [[CrossRef](#)]
98. Saw, L.H.; Ye, Y.; Tay, A.A. Integration issues of lithium-ion battery into electric vehicles battery pack. *J. Clean. Prod.* **2016**, *113*, 1032–1045. [[CrossRef](#)]
99. Effat, M.B.; Wu, C.; Ciucci, F. Modeling efforts in the key areas of thermal management and safety of lithium ion battery cells: A mini review. *Asia-Pac. J. Chem. Eng.* **2016**, *11*, 399–406. [[CrossRef](#)]
100. Jaguemont, J.; Boulon, L.; Dubé, Y. A comprehensive review of lithium-ion batteries used in hybrid and electric vehicles at cold temperatures. *Appl. Energy* **2016**, *164*, 99–114. [[CrossRef](#)]
101. Zhang, S.S.; Xu, K.; Jow, T.R. A new approach toward improved low temperature performance of Li-ion battery. *Electrochem. Commun.* **2002**, *4*, 928–932. [[CrossRef](#)]
102. Shiao, H.C.; Chua, D.; Lin, H.P.; Slane, S.; Salomon, M. Low temperature electrolytes for Li-ion PVDF cells. *J. Power Sources* **2000**, *87*, 167–173. [[CrossRef](#)]
103. Jaguemont, J.; Boulon, L.; Dube, Y.; Martel, F. Thermal Management of a Hybrid Electric Vehicle in Cold Weather. *IEEE Trans. Energy Convers.* **2016**, *31*, 1110–1120. [[CrossRef](#)]
104. Sarre, G.; Blanchard, P.; Broussely, M. Aging of lithium-ion batteries. *J. Power Sources* **2004**, *127*, 65–71 [[CrossRef](#)]
105. Vetter, J.; Novák, P.; Wagner, M.R.; Veit, C.; Möller, K.C.; Besenhard, J.O.; Winter, M.; Wohlfahrt-Mehrens, M.; Vogler, C.; Hammouche, A. Ageing mechanisms in lithium-ion batteries. *J. Power Sources* **2005**, *147*, 269–281. [[CrossRef](#)]
106. Abraham, D.P.; Reynolds, E.M.; Sammann, E.; Jansen, A.N.; Dees, D.W. Aging characteristics of high-power lithium-ion cells with LiNi_{0.8}Co_{0.15}Al_{0.05}O₂ and Li₄/3Ti₅/3O₄ electrodes. *Electrochim. Acta* **2005**, *51*, 502–510. [[CrossRef](#)]
107. Li, J.; Murphy, E.; Winnick, J.; Kohl, P.A. Studies on the cycle life of commercial lithium ion batteries during rapid charge-discharge cycling. *J. Power Sources* **2001**, *102*, 294–301. [[CrossRef](#)]
108. Lu, P.; Li, C.; Schneider, E.W.; Harris, S.J. Chemistry, impedance, and morphology evolution in solid electrolyte interphase films during formation in lithium ion batteries. *J. Phys. Chem. C* **2014**, *118*, 896–903. [[CrossRef](#)]
109. Zhang, S.S.; Xu, K.; Jow, T.R. Low temperature performance of graphite electrode in Li-ion cells. *Electrochim. Acta* **2002**, *48*, 241–246. [[CrossRef](#)]
110. Ji, Y.; Zhang, Y.; Wang, C.Y. Li-Ion Cell Operation at Low Temperatures. *J. Electrochem. Soc.* **2013**, *160*, A636–A649. [[CrossRef](#)]
111. Aifantis, K.E.; Hackney, S.A.; Kumar, R.V. *High Energy Density Lithium Batteries*; Wiley: Hoboken, NJ, USA, 2010.
112. Reddy, T.B. *Linden's Handbook of Batteries*, 4th ed.; McGraw-Hill: New York, NY, USA, 2011.
113. Westbrook, M.H. *The Electric Car: Development and Future of Battery, Hybrid and Fuel-Cell Cars*; The Institution of Engineering and Technology (IET), Michael Faraday House: Stevenage, UK, 2001. [[CrossRef](#)]
114. Larminie, J.; Lowry, J. *Electric Vehicle Technology Explained*; John Wiley and Sons, Ltd.: Chichester, UK, 2012.
115. Shim, J.; Kosteki, R.; Richardson, T.; Song, X.; Striebel, K.A. Electrochemical analysis for cycle performance and capacity fading of a lithium-ion battery cycled at elevated temperature. *J. Power Sources* **2002**, *112*, 222–230. [[CrossRef](#)]
116. Tan, L.; Zhang, L.; Sun, Q.; Shen, M.; Qu, Q.; Zheng, H. Capacity loss induced by lithium deposition at graphite anode for LiFePO₄/graphite cell cycling at different temperatures. *Electrochim. Acta* **2013**, *111*, 802–808. [[CrossRef](#)]
117. Barré, A.; Deguilhem, B.; Grolleau, S.; Gérard, M.; Suard, F.; Riu, D. A review on lithium-ion battery ageing mechanisms and estimations for automotive applications. *J. Power Sources* **2013**, *241*, 680–689. [[CrossRef](#)]
118. Santhanagopalan, S.; Zhang, Q.; Kumaresan, K.; White, R.E. Parameter Estimation and Life Modeling of Lithium-Ion Cells. *J. Electrochem. Soc.* **2008**, *155*, A345. [[CrossRef](#)]
119. Peng, P.; Jiang, F. Thermal behavior analyses of stacked prismatic LiCoO₂ lithium-ion batteries during oven tests. *Int. J. Heat Mass Transf.* **2015**, *88*, 411–423. [[CrossRef](#)]
120. Ye, J.; Chen, H.; Wang, Q.; Huang, P.; Sun, J.; Lo, S. Thermal behavior and failure mechanism of lithium ion cells during overcharge under adiabatic conditions. *Appl. Energy* **2016**, *182*, 464–474. [[CrossRef](#)]
121. Shah, K.; Chalise, D.; Jain, A. Experimental and theoretical analysis of a method to predict thermal runaway in Li-ion cells. *J. Power Sources* **2016**, *330*, 167–174. [[CrossRef](#)]
122. Feng, X.; Fang, M.; He, X.; Ouyang, M.; Lu, L.; Wang, H.; Zhang, M. Thermal runaway features of large format prismatic lithium ion battery using extended volume accelerating rate calorimetry. *J. Power Sources* **2014**, *255*, 294–301. [[CrossRef](#)]
123. Yang, N.; Zhang, X.; Shang, B.; Li, G. Unbalanced discharging and aging due to temperature differences among the cells in a lithium-ion battery pack with parallel combination. *J. Power Sources* **2016**, *306*, 733–741. [[CrossRef](#)]
124. Pesaran, A.A. Battery thermal models for hybrid vehicle simulations. *J. Power Sources* **2002**, *110*, 377–382. [[CrossRef](#)]
125. Khateeb, S.A.; Amiruddin, S.; Farid, M.; Selman, J.R.; Al-Hallaj, S. Thermal management of Li-ion battery with phase change material for electric scooters: Experimental validation. *J. Power Sources* **2005**, *142*, 345–353. [[CrossRef](#)]
126. Feng, X.; Xu, C.; He, X.; Wang, L.; Zhang, G.; Ouyang, M. Mechanisms for the evolution of cell variations within a LiNi_x-Co_yMn_zO₂/graphite lithium-ion battery pack caused by temperature non-uniformity. *J. Clean. Prod.* **2018**, *205*, 447–462. [[CrossRef](#)]
127. Pesaran, A. Battery Thermal Management in EVs and HEVs: Issues and Solutions. In Proceedings of the Advanced Automotive Battery Conference, Las Vegas, NA, USA, 5–8 February 2001; p. 10.
128. Wang, T.; Tseng, K.J.; Zhao, J.; Wei, Z. Thermal investigation of lithium-ion battery module with different cell arrangement structures and forced air-cooling strategies. *Appl. Energy* **2014**, *134*, 229–238. [[CrossRef](#)]

129. Sun, H.; Dixon, R. Development of cooling strategy for an air cooled lithium-ion battery pack. *J. Power Sources* **2014**, *272*, 404–414. [[CrossRef](#)]
130. Chen, K.; Song, M.; Wei, W.; Wang, S. Structure optimization of parallel air-cooled battery thermal management system with U-type flow for cooling efficiency improvement. *Energy* **2018**, *145*, 603–613. [[CrossRef](#)]
131. Huber, C.; Kuhn, R. Thermal management of batteries for electric vehicles. In *Advances in Battery Technologies for Electric Vehicles*; Elsevier: Amsterdam, The Netherlands, 2015; pp. 327–358. [[CrossRef](#)]
132. Yu, X.; Lu, Z.; Zhang, L.; Wei, L.; Cui, X.; Jin, L. Experimental study on transient thermal characteristics of stagger-arranged lithium-ion battery pack with air cooling strategy. *Int. J. Heat Mass Transf.* **2019**, *143*, 118576. [[CrossRef](#)]
133. Zhou, H.; Zhou, F.; Xu, L.; Kong, J.; Yang, Q. Thermal performance of cylindrical Lithium-ion battery thermal management system based on air distribution pipe. *Int. J. Heat Mass Transf.* **2019**, *131*, 984–998. [[CrossRef](#)]
134. Karimi, G.; Li, X. Thermal management of lithium-ion batteries for electric vehicles. *Int. J. Energy Res.* **2013**, *37*, 13–24. [[CrossRef](#)]
135. Li, X.; He, F.; Ma, L. Thermal management of cylindrical batteries investigated using wind tunnel testing and computational fluid dynamics simulation. *J. Power Sources* **2013**, *238*, 395–402. [[CrossRef](#)]
136. Ji, Y.; Wang, C.Y. Heating strategies for Li-ion batteries operated from subzero temperatures. *Electrochim. Acta* **2013**, *107*, 664–674. [[CrossRef](#)]
137. Chen, P.; Lu, Z.; Ji, L.; Li, Y. Design of the control scheme of power battery low temperature charging heating based on the real vehicle applications. In Proceedings of the 2013 IEEE Vehicle Power and Propulsion Conference (VPPC), Beijing, China, 15–18 October 2013; Volume 4, pp. 105–110. [[CrossRef](#)]
138. Chen, K.H.; Han, T.; Khalighi, B.; Klaus, P. Air cooling concepts for Li-ion battery pack in cell level. In Proceedings of the ASME 2017 Heat Transfer Summer Conference, Bellevue, WA, USA, 9–12 July 2017; Volume 1. [[CrossRef](#)]
139. Peng, X.; Cui, X.; Liao, X.; Garg, A. A thermal investigation and optimization of an air-cooled lithium-ion battery pack. *Energies* **2020**, *13*, 2956. [[CrossRef](#)]
140. Wang, H.; He, F.; Ma, L. Experimental and modeling study of controller-based thermal management of battery modules under dynamic loads. *Int. J. Heat Mass Transf.* **2016**, *103*, 154–164. [[CrossRef](#)]
141. He, F.; Wang, H.; Ma, L. Experimental demonstration of active thermal control of a battery module consisting of multiple Li-ion cells. *Int. J. Heat Mass Transf.* **2015**, *91*, 630–639. [[CrossRef](#)]
142. Saw, L.H.; Ye, Y.; Tay, A.A.; Chong, W.T.; Kuan, S.H.; Yew, M.C. Computational fluid dynamic and thermal analysis of Lithium-ion battery pack with air cooling. *Appl. Energy* **2016**, *177*, 783–792. [[CrossRef](#)]
143. Fan, L.; Khodadadi, J.M.; Pesaran, A.A. A parametric study on thermal management of an air-cooled lithium-ion battery module for plug-in hybrid electric vehicles. *J. Power Sources* **2013**, *238*, 301–312. [[CrossRef](#)]
144. Buidin, T.I.C.; Mariasiu, F. Modeling approach of an air-based battery thermal management system for an electric vehicle. *Appl. Sci.* **2021**, *11*, 7089. [[CrossRef](#)]
145. Yang, N.; Zhang, X.; Li, G.; Hua, D. Assessment of the forced air-cooling performance for cylindrical lithium-ion battery packs: A comparative analysis between aligned and staggered cell arrangements. *Appl. Therm. Eng.* **2015**, *80*, 55–65. [[CrossRef](#)]
146. Choi, Y.S.; Kang, D.M. Prediction of thermal behaviors of an air-cooled lithium-ion battery system for hybrid electric vehicles. *J. Power Sources* **2014**, *270*, 273–280. [[CrossRef](#)]
147. Giuliano, M.R.; Prasad, A.K.; Advani, S.G. Experimental study of an air-cooled thermal management system for high capacity lithium-titanate batteries. *J. Power Sources* **2012**, *216*, 345–352. [[CrossRef](#)]
148. Park, S.; Jung, D. Battery cell arrangement and heat transfer fluid effects on the parasitic power consumption and the cell temperature distribution in a hybrid electric vehicle. *J. Power Sources* **2013**, *227*, 191–198. [[CrossRef](#)]
149. Karimi, G.; Dehghan, A.R. Thermal analysis of high-power lithium-ion battery packs using flow network approach. *Int. J. Energy Res.* **2014**, *38*, 1793–1811. [[CrossRef](#)]
150. Saw, L.H.; Tay, A.A.; Zhang, L.W. Thermal management of lithium-ion battery pack with liquid cooling. In Proceedings of the Annual IEEE Semiconductor Thermal Measurement and Management Symposium 2015, San Jose, CA, USA, 15–19 March 2015; Volume 2015, pp. 298–302. [[CrossRef](#)]
151. Beheshti, A.; Shanbedi, M.; Heris, S.Z. Heat transfer and rheological properties of transformer oil-oxidized MWCNT nanofluid. *J. Therm. Anal. Calorim.* **2014**, *118*, 1451–1460. [[CrossRef](#)]
152. Huo, Y.; Rao, Z. The numerical investigation of nanofluid based cylinder battery thermal management using lattice Boltzmann method. *Int. J. Heat Mass Transf.* **2015**, *91*, 374–384. [[CrossRef](#)]
153. Deng, Y.; Feng, C.; E, J.; Zhu, H.; Chen, J.; Wen, M.; Yin, H. Effects of different coolants and cooling strategies on the cooling performance of the power lithium ion battery system: A review. *Appl. Therm. Eng.* **2018**, *142*, 10–29. [[CrossRef](#)]
154. Al-Zareer, M.; Dincer, I.; Rosen, M.A. Novel thermal management system using boiling cooling for high-powered lithium-ion battery packs for hybrid electric vehicles. *J. Power Sources* **2017**, *363*, 291–303. [[CrossRef](#)]
155. Al-Zareer, M.; Dincer, I.; Rosen, M.A. Electrochemical modeling and performance evaluation of a new ammonia-based battery thermal management system for electric and hybrid electric vehicles. *Electrochim. Acta* **2017**, *247*, 171–182. [[CrossRef](#)]
156. Van Gils, R.W.; Danilov, D.; Notten, P.H.; Speetjens, M.F.; Nijmeijer, H. Battery thermal management by boiling heat-transfer. *Energy Convers. Manag.* **2014**, *79*, 9–17. [[CrossRef](#)]

157. Hirano, H.; Tajima, T.; Hasegawa, T.; Sekiguchi, T.; Uchino, M. Boiling liquid battery cooling for electric vehicle. In Proceedings of the IEEE Transportation Electrification Conference and Expo, ITEC Asia-Pacific 2014—Conference Proceedings, Beijing, China, 31 August–3 September 2014; pp. 1–4. [\[CrossRef\]](#)
158. Huo, Y.; Rao, Z.; Liu, X.; Zhao, J. Investigation of power battery thermal management by using mini-channel cold plate. *Energy Convers. Manag.* **2015**, *89*, 387–395. [\[CrossRef\]](#)
159. Kalkan, O.; Celen, A.; Bakirci, K.; Dalkilic, A.S. Experimental investigation of thermal performance of novel cold plate design used in a Li-ion pouch-type battery. *Appl. Therm. Eng.* **2021**, *191*, 116885. [\[CrossRef\]](#)
160. Li, Y.; Guo, H.; Qi, F.; Guo, Z.; Li, M.; Bertling Tjernberg, L. Investigation on liquid cold plate thermal management system with heat pipes for LiFePO₄ battery pack in electric vehicles. *Appl. Therm. Eng.* **2021**, *185*, 116382. [\[CrossRef\]](#)
161. Chen, K.; Chen, Y.; Song, M.; Wang, S. Multi-parameter structure design of parallel mini-channel cold plate for battery thermal management. *Int. J. Energy Res.* **2020**, *44*, 4321–4334. [\[CrossRef\]](#)
162. Deng, T.; Zhang, G.; Ran, Y. Study on thermal management of rectangular Li-ion battery with serpentine-channel cold plate. *Int. J. Heat Mass Transf.* **2018**, *125*, 143–152. [\[CrossRef\]](#)
163. Zhou, H.; Zhou, F.; Zhang, Q.; Wang, Q.; Song, Z. Thermal management of cylindrical lithium-ion battery based on a liquid cooling method with half-helical duct. *Appl. Therm. Eng.* **2019**, *162*, 114257. [\[CrossRef\]](#)
164. Jin, L.W.; Lee, P.S.; Kong, X.X.; Fan, Y.; Chou, S.K. Ultra-thin minichannel LCP for EV battery thermal management. *Appl. Energy* **2014**, *113*, 1786–1794. [\[CrossRef\]](#)
165. Krüger, I.L.; Limperich, D.; Schmitz, G. Energy Consumption Of Battery Cooling In Hybrid Electric Vehicles. In Proceedings of the International Refrigeration and Air Conditioning Conference, Purdue, IN, USA, 16–19 July 2012; pp. 1–10.
166. Chen, D.; Jiang, J.; Kim, G.H.; Yang, C.; Pesaran, A. Comparison of different cooling methods for lithium ion battery cells. *Appl. Therm. Eng.* **2016**, *94*, 846–854. [\[CrossRef\]](#)
167. Thakur, A.K.; Prabakaran, R.; Elkadeem, M.R.; Sharshir, S.W.; Arıcı, M.; Wang, C.; Zhao, W.; Hwang, J.Y.; Saidur, R. A state of art review and future viewpoint on advance cooling techniques for Lithium-ion battery system of electric vehicles. *J. Energy Storage* **2020**, *32*, 101771. [\[CrossRef\]](#)
168. Tran, T.H.; Harmand, S.; Desmet, B.; Filangi, S. Experimental investigation on the feasibility of heat pipe cooling for HEV/EV lithium-ion battery. *Appl. Therm. Eng.* **2014**, *63*, 551–558. [\[CrossRef\]](#)
169. Huang, J.; Shoai Naini, S.; Miller, R.; Rizzo, D.; Sebeck, K.; Shurin, S.; Wagner, J. Development of a heat pipe-based battery thermal management system for hybrid electric vehicles. *Proc. Inst. Mech. Eng. Part D J. Automob. Eng.* **2020**, *234*, 1532–1543. [\[CrossRef\]](#)
170. Rao, Z.; Wang, S.; Wu, M.; Lin, Z.; Li, F. Experimental investigation on thermal management of electric vehicle battery with heat pipe. *Energy Convers. Manag.* **2013**, *65*, 92–97. [\[CrossRef\]](#)
171. Qu, J.; Zhao, J.; Rao, Z. Experimental investigation on thermal performance of multi-layers three-dimensional oscillating heat pipes. *Int. J. Heat Mass Transf.* **2017**, *115*, 810–819. [\[CrossRef\]](#)
172. Zou, H.; Wang, W.; Zhang, G.; Qin, F.; Tian, C.; Yan, Y. Experimental investigation on an integrated thermal management system with heat pipe heat exchanger for electric vehicle. *Energy Convers. Manag.* **2016**, *118*, 88–95. [\[CrossRef\]](#)
173. Chen, K.; Hou, J.; Song, M.; Wang, S.; Wu, W.; Zhang, Y. Design of battery thermal management system based on phase change material and heat pipe. *Appl. Therm. Eng.* **2021**, *188*, 116665. [\[CrossRef\]](#)
174. Murali, G.; Sravya, G.S.; Jaya, J.; Naga Vamsi, V. A review on hybrid thermal management of battery packs and its cooling performance by enhanced PCM. *Renew. Sustain. Energy Rev.* **2021**, *150*, 111513. [\[CrossRef\]](#)
175. Pielichowska, K.; Pielichowski, K. Phase change materials for thermal energy storage. *Prog. Mater. Sci.* **2014**, *65*, 67–123. [\[CrossRef\]](#)
176. Chen, J.; Kang, S.; E, J.; Huang, Z.; Wei, K.; Zhang, B.; Zhu, H.; Deng, Y.; Zhang, F.; Liao, G. Effects of different phase change material thermal management strategies on the cooling performance of the power lithium ion batteries: A review. *J. Power Sources* **2019**, *442*, 227228. [\[CrossRef\]](#)
177. Kiani, M.; Omiddezyani, S.; Houshfar, E.; Miremadi, S.R.; Ashjaee, M.; Mahdavi Nejad, A. Lithium-ion battery thermal management system with Al₂O₃/AgO/CuO nanofluids and phase change material. *Appl. Therm. Eng.* **2020**, *180*, 115840. [\[CrossRef\]](#)
178. Babapoor, A.; Haghighi, A.; Jokar, S.M.; Mezjin, M.A. The Performance Enhancement of Paraffin as a PCM During the Solidification Process: Utilization of Graphene and Metal Oxide Nanoparticles. *IJCCE* **2020**. [\[CrossRef\]](#)
179. Mezjin, M.A.; Karimi, G.; Medi, B.; Babapoor, A.; Paar, M. Passive thermal management of a lithium-ion battery using carbon fiber loaded phase change material: Comparison and optimization. *IJCCE* **2020**. [\[CrossRef\]](#)
180. Babapoor, A.; Azizi, M.; Karimi, G. Thermal management of a Li-ion battery using carbon fiber-PCM composites. *Appl. Therm. Eng.* **2015**, *82*, 281–290. [\[CrossRef\]](#)
181. Bashirpour-Bonab, H. Thermal behavior of lithium batteries used in electric vehicles using phase change materials. *Int. J. Energy Res.* **2020**, *44*, 12583–12591. [\[CrossRef\]](#)
182. Jiang, K.; Liao, G.; E, J.; Zhang, F.; Chen, J.; Leng, E. Thermal management technology of power lithium-ion batteries based on the phase transition of materials: A review. *J. Energy Storage* **2020**, *32*, 101816. [\[CrossRef\]](#)
183. Alipanah, M.; Li, X. Numerical studies of lithium-ion battery thermal management systems using phase change materials and metal foams. *Int. J. Heat Mass Transf.* **2016**, *102*, 1159–1168. [\[CrossRef\]](#)

184. Karimi, G.; Azizi, M.; Babapoor, A. Experimental study of a cylindrical lithium ion battery thermal management using phase change material composites. *J. Energy Storage* **2016**, *8*, 168–174. [[CrossRef](#)]
185. Golestaneh, S.I.; Karimi, G.; Babapoor, A.; Torabi, F. Thermal performance of co-electrospun fatty acid nanofiber composites in the presence of nanoparticles. *Appl. Energy* **2018**, *212*, 552–564. [[CrossRef](#)]
186. Haghighi, A.; Babapoor, A.; Azizi, M.; Javanshir, Z. Optimization of the thermal performance of PCM nanocomposites. *Res. Artic. J. Energy Manag. Technol. (JEMT)* **2020**, *4*, 14.
187. Jaguemont, J.; Van Mierlo, J. A comprehensive review of future thermal management systems for battery-electrified vehicles. *J. Energy Storage* **2020**, *31*, 101551. [[CrossRef](#)]
188. Fathabadi, H. High thermal performance lithium-ion battery pack including hybrid active-passive thermal management system for using in hybrid/electric vehicles. *Energy* **2014**, *70*, 529–538. [[CrossRef](#)]
189. Yue, Q.L.; He, C.X.; Jiang, H.R.; Wu, M.C.; Zhao, T.S. A hybrid battery thermal management system for electric vehicles under dynamic working conditions. *Int. J. Heat Mass Transf.* **2021**, *164*, 120528. [[CrossRef](#)]
190. Xu, Y.; Li, X.; Liu, X.; Wang, Y.; Wu, X.; Zhou, D. Experiment investigation on a novel composite silica gel plate coupled with liquid-cooling system for square battery thermal management. *Appl. Therm. Eng.* **2021**, *184*, 116217. [[CrossRef](#)]
191. Yang, W.; Zhou, F.; Zhou, H.; Wang, Q.; Kong, J. Thermal performance of cylindrical lithium-ion battery thermal management system integrated with mini-channel liquid cooling and air cooling. *Appl. Therm. Eng.* **2020**, *175*, 115331. [[CrossRef](#)]
192. Bamdezh, M.A.; Molaeimanesh, G.R.; Zanganeh, S. Role of foam anisotropy used in the phase-change composite material for the hybrid thermal management system of lithium-ion battery. *J. Energy Storage* **2020**, *32*, 101778. [[CrossRef](#)]
193. Ling, Z.; Wang, F.; Fang, X.; Gao, X.; Zhang, Z. A hybrid thermal management system for lithium ion batteries combining phase change materials with forced-air cooling. *Appl. Energy* **2015**, *148*, 403–409. [[CrossRef](#)]
194. Wang, Y.; Peng, P.; Cao, W.; Dong, T.; Zheng, Y.; Lei, B.; Shi, Y.; Jiang, F. Experimental study on a novel compact cooling system for cylindrical lithium-ion battery module. *Appl. Therm. Eng.* **2020**, *180*, 115772. [[CrossRef](#)]
195. Botte, G.G.; Subramanian, V.R.; White, R.E. Mathematical modeling of secondary lithium batteries. *Electrochim. Acta* **2000**, *45*, 2595–2609. [[CrossRef](#)]
196. Smith, K.; Wang, C.Y. Power and thermal characterization of a lithium-ion battery pack for hybrid-electric vehicles. *J. Power Sources* **2006**, *160*, 662–673. [[CrossRef](#)]
197. Liu, G.; Ouyang, M.; Lu, L.; Li, J.; Han, X. Analysis of the heat generation of lithium-ion battery during charging and discharging considering different influencing factors. *J. Therm. Anal. Calorim.* **2014**, *116*, 1001–1010. [[CrossRef](#)]
198. Ramadesigan, V.; Northrop, P.W.C.; De, S.; Santhanagopalan, S.; Braatz, R.D.; Subramanian, V.R. Modeling and Simulation of Lithium-Ion Batteries from a Systems Engineering Perspective. *J. Electrochem. Soc.* **2012**, *159*, R31–R45. [[CrossRef](#)]
199. Chen, X.; Shen, W.; Cao, Z.; Kapoor, A. Adaptive gain sliding mode observer for state of charge estimation based on combined battery equivalent circuit model. *Comput. Chem. Eng.* **2014**, *64*, 114–123. [[CrossRef](#)]
200. Hariharan, K.S.; Kumar, V.S. A nonlinear equivalent circuit model for lithium ion cells. *J. Power Sources* **2013**, *222*, 210–217. [[CrossRef](#)]
201. Fuller, T.F.; Doyle, M.; Newman, J. Simulation and Optimization of the Dual Lithium Ion Insertion Cell. *J. Electrochem. Soc.* **1994**, *141*, 1–10. [[CrossRef](#)]
202. Santhanagopalan, S.; Guo, Q.; Ramadass, P.; White, R.E. Review of models for predicting the cycling performance of lithium ion batteries. *J. Power Sources* **2006**, *156*, 620–628. [[CrossRef](#)]
203. Subramanian, V.R.; Ritter, J.A.; White, R.E. Approximate Solutions for Galvanostatic Discharge of Spherical Particles I. Constant Diffusion Coefficient. *J. Electrochem. Soc.* **2001**, *148*, E444. [[CrossRef](#)]
204. Guo, M.; Sikha, G.; White, R.E. Single-Particle Model for a Lithium-Ion Cell: Thermal Behavior. *J. Electrochem. Soc.* **2011**, *158*, A122. [[CrossRef](#)]
205. Xu, M.; Zhang, Z.; Wang, X.; Jia, L.; Yang, L. A pseudo three-dimensional electrochemical-thermal model of a prismatic LiFePO₄ battery during discharge process. *Energy* **2015**, *80*, 303–317. [[CrossRef](#)]
206. Sarkar, J.; Bhattacharyya, S. Application of graphene and graphene-based materials in clean energy-related devices Minghui. *Arch. Thermodyn.* **2012**, *33*, 23–40. [[CrossRef](#)]
207. Zhang, H.; Li, C.; Zhang, R.; Lin, Y.; Fang, H. Thermal analysis of a 6s4p Lithium-ion battery pack cooled by cold plates based on a multi-domain modeling framework. *Appl. Therm. Eng.* **2020**, *173*, 115216. [[CrossRef](#)]
208. Kwon, K.H.; Shin, C.B.; Kang, T.H.; Kim, C.S. A two-dimensional modeling of a lithium-polymer battery. *J. Power Sources* **2006**, *163*, 151–157. [[CrossRef](#)]
209. Lee, K.; Smith, K.; Kim, G. A three-dimensional thermal-electrochemical coupled model for spirally wound large-format lithium-ion batteries. In Proceedings of the Space Power Workshop, Los Angeles, CA, USA, 18–21 April 2011.
210. Kim, G.H.; Smith, K. Three-Dimensional Lithium-Ion Battery Model. In Proceedings of the 4th International Symposium on Large Lithium ion Battery Technology and Application, Tampa, FL, USA, 12–14 May 2008.
211. Samimi, F.; Babapoor, A.; Azizi, M.; Karimi, G. Thermal management analysis of a Li-ion battery cell using phase change material loaded with carbon fibers. *Energy* **2016**, *96*, 355–371. [[CrossRef](#)]
212. Yang, Y.; Bilgin, B.; Kasprzak, M.; Nalakath, S.; Sadek, H.; Preindl, M.; Cotton, J.; Schofield, N.; Emadi, A. Thermal management of electric machines. *IET Electr. Syst. Transp.* **2017**, *7*, 104–116. [[CrossRef](#)]
213. Bilgin, B.; Emadi, A. Electric motors in electrified transportation. *IEEE Power Electron. Mag.* **2014**, *1*, 10–17. [[CrossRef](#)]

214. Staton, D.A.; Popescu, M.; Hawkins, D.; Boglietti, A.; Cavagnino, A. Influence of different end region cooling arrangements on end-winding heat transfer coefficients in electrical machines. In Proceedings of the 2010 IEEE Energy Conversion Congress and Exposition, ECCE 2010—Proceedings, Atlanta, GA, USA, 12–16 September 2010; pp. 1298–1305. [[CrossRef](#)]
215. Senda, K.; Namikawa, M.; Hayakawa, Y. Electrical steels for advanced automobiles - Core materials for motors, generators, and high-frequency reactors. *JFE Tech. Rep.* **2004**, *4*, 67–73.
216. Gerada, D.; Mebarki, A.; Brown, N.L.; Gerada, C.; Cavagnino, A.; Boglietti, A. High-speed electrical machines: Technologies, trends, and developments. *IEEE Trans. Ind. Electron.* **2014**, *61*, 2946–2959. [[CrossRef](#)]
217. Nategh, S.; Krings, A.; Huang, Z.; Wallmark, O.; Leksell, M.; Lindenmo, M. Evaluation of stator and rotor lamination materials for thermal management of a PMaSRM. In Proceedings of the 2012 20th International Conference on Electrical Machines, ICEM 2012, Marseille, France, 2–5 September 2012; pp. 1309–1314. [[CrossRef](#)]
218. Gai, Y.; Kimiabeigi, M.; Chuan Chong, Y.; Widmer, J.D.; Deng, X.; Popescu, M.; Goss, J.; Staton, D.A.; Steven, A. Cooling of automotive traction motors: Schemes, examples, and computation methods. *IEEE Trans. Ind. Electron.* **2019**, *66*, 1681–1692. [[CrossRef](#)]
219. Li, H. Cooling of a permanent magnet electric motor with a centrifugal impeller. *Int. J. Heat Mass Transf.* **2010**, *53*, 797–810. [[CrossRef](#)]
220. Farsane, K.; Desevaux, P.; Panday, P.K. Experimental study of the cooling of a closed type electric motor. *Appl. Therm. Eng.* **2000**, *20*, 1321–1334. [[CrossRef](#)]
221. Dessouky, Y.G.; Williams, B.W.; Fletcher, J.E. Cooling enhancement of electric motors. *IEE Proc. Electr. Power Appl.* **1998**, *145*, 57–60. [[CrossRef](#)]
222. Lee, Y.; Hahn, S.Y.; Ken Kauh, S. Thermal analysis of induction motor with forced cooling channels. *IEEE Trans. Magn.* **2000**, *36*, 1394–1397. [[CrossRef](#)]
223. Galea, M.; Gerada, C.; Raminoso, T.; Wheeler, P. A thermal improvement technique for the phase windings of electrical machines. *IEEE Trans. Ind. Appl.* **2012**, *48*, 79–87. [[CrossRef](#)]
224. Vlach, R.; Grepl, R.; Krejci, P. Control of stator winding slot cooling by water using prediction of heating. In Proceedings of the 2007 4th IEEE International Conference on Mechatronics, ICM 2007, Kumamoto, Japan, 8–10 May 2007; pp. 1–5. [[CrossRef](#)]
225. Rhebergen, C.; Bilgin, B.; Emadi, A.; Rowan, E.; Lo, J. Enhancement of electric motor thermal management through axial cooling methods: A materials approach. In Proceedings of the 2015 IEEE Energy Conversion Congress and Exposition (ECCE 2015), Montreal, QC, Canada, 20–24 September 2015; pp. 5682–5688. [[CrossRef](#)]
226. Semidey, S.A.; Mayor, J.R. Experimentation of an electric machine technology demonstrator incorporating direct winding heat exchangers. *IEEE Trans. Ind. Electron.* **2014**, *61*, 5771–5778. [[CrossRef](#)]
227. Boglietti, A.; Cavagnino, A. Analysis of the endwinding cooling effects in TEFC induction motors. *IEEE Trans. Ind. Appl.* **2007**, *43*, 1214–1222. [[CrossRef](#)]
228. Guechi, M.R.; Desevaux, P.; Baucour, P.; Espanet, C.; Brunel, R.; Poirot, M. On the improvement of the thermal behavior of electric motors. In Proceedings of the 2013 IEEE Energy Conversion Congress and Exposition (ECCE 2013), Denver, CO, USA, 15–19 September 2013; pp. 1512–1517. [[CrossRef](#)]
229. Deisenroth, D.C.; Ohadi, M. Thermal management of high-power density electric motors for electrification of aviation and beyond. *Energies* **2019**, *12*, 1–18. [[CrossRef](#)]
230. Alatalo, M.; Lundmark, S.T.; Grunditz, E.A. Evaluation of Three Cooling Concepts for an Electric Vehicle Motor—3D Models. In Proceedings of the 2020 International Conference on Electrical Machines (ICEM), Gothenburg, Sweden, 23–26 August 2020; Volume 1, pp. 867–873. [[CrossRef](#)]
231. Rostami, N.; Feyzi, M.R.; Pyrhonen, J.; Parviainen, A.; Niemela, M. Lumped-parameter thermal model for axial flux permanent magnet machines. *IEEE Trans. Magn.* **2013**, *49*, 1178–1184. [[CrossRef](#)]
232. Mo, L.; Zhang, T.; Lu, Q. Thermal Analysis of a Flux-Switching Permanent-Magnet Double-Rotor Machine with a 3-D Thermal Network Model. *IEEE Trans. Appl. Supercond.* **2019**, *29*. [[CrossRef](#)]
233. Li, G.; Ojeda, J.; Hoang, E.; Gabsi, M.; Lecrivain, M. Thermal-electromagnetic analysis for driving cycles of embedded flux-switching permanent-magnet motors. *IEEE Trans. Veh. Technol.* **2012**, *61*, 140–151. [[CrossRef](#)]
234. Borges, S.S.; Cezario, C.A.; Kunz, T.T. Design of water cooled electric motors using CFD and thermography techniques. In Proceedings of the 2008 International Conference on Electrical Machines (ICEM'08), Vilamoura, Portugal, 6–9 September 2008; pp. 1–6. [[CrossRef](#)]
235. Lohrasbi, S.; Hammer, R.; Essl, W.; Reiss, G.; Defregger, S.; Sanz, W. A comprehensive review on the core thermal management improvement concepts in power electronics. *IEEE Access* **2020**, *8*, 166880–166906. [[CrossRef](#)]
236. Laloya, E.; Lucía, Ó.; Sarnago, H.; Burdío, J.M. Heat Management in Power Converters: From State of the Art to Future Ultrahigh Efficiency Systems. *IEEE Trans. Power Electron.* **2016**, *31*, 7896–7908. [[CrossRef](#)]
237. Prasher, R. Thermal interface materials: Historical perspective, status, and future directions. *Proc. IEEE* **2006**, *94*, 1571–1586. [[CrossRef](#)]
238. Ma, H.; Gao, B.; Wang, M.; Yuan, Z.; Shen, J.; Zhao, J.; Feng, Y. Strategies for enhancing thermal conductivity of polymer-based thermal interface materials: A review. *J. Mater. Sci.* **2021**, *56*, 1064–1086. [[CrossRef](#)]
239. Guo, X.; Cheng, S.; Cai, W.; Zhang, Y.; Zhang, X.-A. A review of carbon-based thermal interface materials: Mechanism, thermal measurements and thermal properties. *Mater. Des.* **2021**, *209*, 109936. [[CrossRef](#)]

240. Swamy, M.C.; Satyanarayan. A Review of the Performance and Characterization of Conventional and Promising Thermal Interface Materials for Electronic Package Applications. *J. Electron. Mater.* **2019**, *48*, 7623–7634. [[CrossRef](#)]
241. Jones-Jackson, S.; Rodriguez, R.; Emadi, A. Jet Impingement Cooling in Power Electronics for Electrified Automotive Transportation: Current Status and Future Trends. *IEEE Trans. Power Electron.* **2021**, *36*, 10420–10435. [[CrossRef](#)]
242. Li, X.; Lv, L.; Wang, X.; Li, J. Transient thermodynamic response and boiling heat transfer limit of dielectric liquids in a two-phase closed direct immersion cooling system. *Therm. Sci. Eng. Prog.* **2021**, *25*, 100986. [[CrossRef](#)]
243. Reimers, J.; Dorn-Gomba, L.; Mak, C.; Emadi, A. Automotive Traction Inverters: Current Status and Future Trends. *IEEE Trans. Veh. Technol.* **2019**, *68*, 3337–3350. [[CrossRef](#)]
244. Broughton, J.; Smet, V.; Tummala, R.R.; Joshi, Y.K. Review of Thermal Packaging Technologies for Automotive Power Electronics for Traction Purposes. *J. Electron. Packag. Trans. ASME* **2018**, *140*, 1–11. [[CrossRef](#)]
245. Mochizuki, M.; Nguyen, T.; Mashiko, K.; Saito, Y.; Nguyen, T.; Wuttijumng, V. A Review of Heat Pipe Application Including New Opportunities. *Front. Heat Pipes* **2011**, *2*, 013001. [[CrossRef](#)]
246. Kumar, A.; Kothari, R.; Sahu, S.K.; Kundalwal, S.I. A comparative study and optimization of phase change material based heat sinks for thermal management of electronic components. *J. Energy Storage* **2021**, *43*, 103224. [[CrossRef](#)]
247. Khodadadi, J.M.; Hosseinizadeh, S.F. Nanoparticle-enhanced phase change materials (NEPCM) with great potential for improved thermal energy storage. *Int. Commun. Heat Mass Transf.* **2007**, *34*, 534–543. [[CrossRef](#)]
248. Yang, H.; Li, Y.; Zhang, L.; Zhu, Y. Thermal performance enhancement of phase change material heat sinks for thermal management of electronic devices under constant and intermittent power loads. *Int. J. Heat Mass Transf.* **2021**, *181*, 121899. [[CrossRef](#)]
249. Laitinen, A.; Saari, K.; Kukko, K.; Peltonen, P.; Laurila, E.; Partanen, J.; Vuorinen, V. A computational fluid dynamics study by conjugate heat transfer in OpenFOAM: A liquid cooling concept for high power electronics. *Int. J. Heat Fluid Flow* **2020**, *85*, 108654. [[CrossRef](#)]
250. Al-Waaly, A.A.; Paul, M.C.; Dobson, P. Liquid cooling of non-uniform heat flux of a chip circuit by subchannels. *Appl. Therm. Eng.* **2017**, *115*, 558–574. [[CrossRef](#)]
251. Xie, L.; Yuan, X.; Wang, W. Thermal-Flow Network Modeling for Virtual Prototyping of Power Electronics. *IEEE Trans. Components Packag. Manuf. Technol.* **2021**, *11*, 1282–1291. [[CrossRef](#)]
252. Shams Ghahfarokhi, P.; Kallaste, A.; Belahcen, A.; Vaimann, T. Analytical thermal model and flow network analysis suitable for open self-ventilated machines. *IET Electr. Power Appl.* **2020**, *14*, 929–936. [[CrossRef](#)]
253. Liu, Y.; Peng, J.; Wang, B.; Qin, D.; Ye, M. Bulk temperature prediction of a two-speed automatic transmission for electric vehicles using thermal network method and experimental validation. *Proc. Inst. Mech. Eng. Part D J. Automob. Eng.* **2019**, *233*, 2585–2598. [[CrossRef](#)]
254. Kowalski, T.; Radmehr, A. Thermal analysis of an electronics enclosure: Coupling Flow Network Modeling (FNM) and Computational Fluid Dynamics (CFD). In Proceedings of the Annual IEEE Semiconductor Thermal Measurement and Management Symposium, San Jose, CA, USA, 21–23 March 2000; pp. 60–67. [[CrossRef](#)]
255. European Commission. Commission Regulation (EU) 2017/1151 of 1 June 2017 supplementing Regulation (EC) No 715/2007 of the European Parliament and of the Council on type-approval of motor vehicles with respect to emissions from light passenger and commercial vehicles (Euro 5 a). *Off. J. Eur. Union* **2017**, *175*, 1–643.
256. Yuan, R.; Price, C.; Kasurkar, R.; Spenley, M.; Dutta, N.; Ebrahimi, K. Numerical Investigation of Heat Retention and Warm-Up with Thermal Encapsulation of Powertrain. *SAE Tech. Pap.* **2020**, *2020*, 1–8. [[CrossRef](#)]
257. Minovski, B.; Andrić, J.; Löfdahl, L.; Gullberg, P. A numerical investigation of thermal engine encapsulation concept for a passenger vehicle and its effect on fuel consumption. *Proc. Inst. Mech. Eng. Part D J. Automob. Eng.* **2019**, *233*, 557–571. [[CrossRef](#)]
258. Yuan, R.; Dutta, N.; Sivasankaran, S.; Jansen, W.; Ebrahimi, K. Heat retention analysis with thermal encapsulation of powertrain under natural soak environment. *Int. J. Heat Mass Transf.* **2020**, *147*, 118940. [[CrossRef](#)]
259. Chen, K.H.; Johnson, J.; Merati, P.; Davis, C. Numerical investigation of buoyancy-driven flow in a simplified underhood with open enclosure. *SAE Int. J. Passeng. Cars Mech. Syst.* **2013**, *6*, 805–816. [[CrossRef](#)]
260. Yuan, R.; Sivasankaran, S.; Dutta, N.; Jansen, W.; Ebrahimi, K. Numerical investigation of buoyancy-driven heat transfer within engine bay environment during thermal soak. *Appl. Therm. Eng.* **2020**, *164*, 114525. [[CrossRef](#)]
261. Minovski, B.B.; Löfdahl, L.; Gullberg, P. A 1D Method for Transient Simulations of Cooling Systems with Non-Uniform Temperature and Flow Boundaries Extracted from a 3D CFD Solution. *SAE Tech. Pap.* **2015**, *2015*. [[CrossRef](#)]
262. Liu, Y.; Gao, Q.; Zhang, T.; Cui, C.; Jin, S. Exploration of interactive thermal influence characteristics of power and air conditioning system based on 1D/3D coupling calculation in electric vehicle underhood. *Appl. Therm. Eng.* **2020**, *167*, 114717. [[CrossRef](#)]
263. Chang, T.B.; Sheu, J.J.; Huang, J.W.; Lin, Y.S.; Chang, C.C. Development of a CFD model for simulating vehicle cabin indoor air quality. *Transp. Res. Part D Transp. Environ.* **2018**, *62*, 433–440. [[CrossRef](#)]
264. Hudda, N.; Fruin, S.A. Carbon dioxide accumulation inside vehicles: The effect of ventilation and driving conditions. *Sci. Total. Environ.* **2018**, *610–611*, 1448–1456. [[CrossRef](#)] [[PubMed](#)]
265. Horrein, L.; Bouscayrol, A.; Lhomme, W.; Depature, C. Impact of Heating System on the Range of an Electric Vehicle. *IEEE Trans. Veh. Technol.* **2017**, *66*, 4668–4677. [[CrossRef](#)]

266. Jeffers, M.A.; Chaney, L.; Rugh, J.P. Climate Control Load Reduction Strategies for Electric Drive Vehicles in Cold Weather. *SAE Int. J. Passeng. Cars Mech. Syst.* **2016**, *9*, 75–82. [[CrossRef](#)]
267. Shin, Y.H.; Sim, S.; Kim, S.C. Performance characteristics of a modularized and integrated PTC heating system for an electric vehicle. *Energies* **2016**, *9*, 18. [[CrossRef](#)]
268. Mastinu, G.; Ploechl, M. (Eds.) *Road and Off-Road Vehicle System Dynamics Handbook*; CRC Press: Boca Raton, FL, USA, 2014. [[CrossRef](#)]
269. Holjevac, N.; Cheli, F.; Gobbi, M. Multi-objective vehicle optimization: Comparison of combustion engine, hybrid and electric powertrains. *Proc. Inst. Mech. Eng. Part D J. Automob. Eng.* **2020**, *234*, 469–487. [[CrossRef](#)]
270. Feng, L.; Hrnjak, P. Experimental Study of an Air Conditioning-Heat Pump System for Electric Vehicles. *SAE Tech. Pap.* **2016**. [[CrossRef](#)]
271. Musser, A.; Hrnjak, P.S. Mobile Heat Pump Exploration Using R445A and. In Proceedings of the International Refrigeration and Air Conditioning Conference, Purdue, IN, USA, 14–17 July 2014.
272. Lajunen, A.; Yang, Y.; Emadi, A. Review of Cabin Thermal Management for Electrified Passenger Vehicles. *IEEE Trans. Veh. Technol.* **2020**, *69*, 6025–6040. [[CrossRef](#)]
273. Danca, P.; Bode, F.; Nastase, I.; Meslem, A. On the Possibility of CFD Modeling of the Indoor Environment in a Vehicle. *Energy Procedia* **2017**, *112*, 656–663. [[CrossRef](#)]
274. Jamin, A.; Bosschaerts, W.; Nastase, I.; Janssens, B. Review of the existing state of the art regarding the use of CFD and human thermophysiological models for the vehicular comfort assessment. *IOP Conf. Ser. Earth Environ. Sci.* **2021**, *664*, 012012. [[CrossRef](#)]
275. Singh, S.; Abbassi, H. 1D/3D transient HVAC thermal modeling of an off-highway machinery cabin using CFD-ANN hybrid method. *Appl. Therm. Eng.* **2018**, *135*, 406–417. [[CrossRef](#)]
276. Warey, A.; Kaushik, S.; Khalighi, B.; Cruse, M.; Venkatesan, G. Data-driven prediction of vehicle cabin thermal comfort: Using machine learning and high-fidelity simulation results. *Int. J. Heat Mass Transf.* **2020**, *148*, 119083. [[CrossRef](#)]
277. Amini, M.R.; Wang, H.; Gong, X.; Liao-Mcpherson, D.; Kolmanovsky, I.; Sun, J. Cabin and battery thermal management of connected and automated hevs for improved energy efficiency using hierarchical model predictive control. *IEEE Trans. Control Syst. Technol.* **2020**, *28*, 1711–1726. [[CrossRef](#)]
278. Torregrosa-Jaime, B.; Bjurling, F.; Corberán, J.M.; Di Sciullo, F.; Payá, J. Transient thermal model of a vehicle's cabin validated under variable ambient conditions. *Appl. Therm. Eng.* **2015**, *75*, 45–53. [[CrossRef](#)]
279. Wu, J.; Jiang, F.; Song, H.; Liu, C.; Lu, B. Analysis and validation of transient thermal model for automobile cabin. *Appl. Therm. Eng.* **2017**, *122*, 91–102. [[CrossRef](#)]
280. Marcos, D.; Pino, F.J.; Bordons, C.; Guerra, J.J. The development and validation of a thermal model for the cabin of a vehicle. *Appl. Therm. Eng.* **2014**, *66*, 646–656. [[CrossRef](#)]
281. Mastinu, G.; Gobbi, M.; Miano, C. *Optimal Design of Complex Mechanical Systems: With Applications to Vehicle Engineering*; Springer: Berlin/Heidelberg, Germany, 2006; pp. 1–359. [[CrossRef](#)]
282. Li, Y.; Du, Y.; Xu, T.; Wu, H.; Zhou, X.; Ling, Z.; Zhang, Z. Optimization of thermal management system for Li-ion batteries using phase change material. *Appl. Therm. Eng.* **2018**, *131*, 766–778. [[CrossRef](#)]
283. Mousavi, M.; Hoque, S.; Rahnamayan, S.; Dincer, I.; Naterer, G.F. Optimal design of an air-cooling system for a Li-Ion battery pack in Electric Vehicles with a genetic algorithm. In Proceedings of the 2011 IEEE Congress of Evolutionary Computation (CEC 2011), New Orleans, LA, USA, 5–8 June 2011; pp. 1848–1855. [[CrossRef](#)]
284. Li, W.; Peng, X.; Xiao, M.; Garg, A.; Gao, L. Multi-objective design optimization for mini-channel cooling battery thermal management system in an electric vehicle. *Int. J. Energy Res.* **2019**, *43*, 3668–3680. [[CrossRef](#)]
285. Li, A.C.T.; Li, W.; Chin, C.M.M.; Garg, A.; Gao, L. Multidisciplinary optimal design of prismatic lithium-ion battery with an improved thermal management system for electric vehicles. *Energy Storage* **2021**, *3*, 1–11. [[CrossRef](#)]
286. Zhang, W.; Liang, Z.; Wu, W.; Ling, G.; Ma, R. Design and optimization of a hybrid battery thermal management system for electric vehicle based on surrogate model. *Int. J. Heat Mass Transf.* **2021**, *174*, 121318. [[CrossRef](#)]
287. Bayraktar, I. Computational simulation methods for vehicle thermal management. *Appl. Therm. Eng.* **2012**, *36*, 325–329. [[CrossRef](#)]
288. Silvas, E.; Hofman, T.; Murgovski, N.; Etman, L.F.; Steinbuch, M. Review of Optimization Strategies for System-Level Design in Hybrid Electric Vehicles. *IEEE Trans. Veh. Technol.* **2016**, *66*, 57–70. [[CrossRef](#)]
289. Fathy, H.K.; Reyer, J.A.; Papalambros, P.Y.; Ulsoy, A.G. On the coupling between the plant and controller optimization problems. *Proc. Am. Control Conf.* **2001**, *3*, 1864–1869. [[CrossRef](#)]