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THERMAL MANAGMENT OF EV, BEV, PHEV AND FCEV VEHICLES

TEPELNÝ MANAGEMENT EV, BEV, PHEV A FCEV VOZIDEL

BACHELOR'S THESIS

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As provided for by the Act No. 111/98 Coll. on higher education institutions and the BUT Study and Examination Regulations, the director of the Institute hereby assigns the following topic of Bachelor's Thesis:

Thermal Management of EV, BEV, PHEV and FCEV vehicles

Brief Description:

It currently seems that different levels of electric mobility will be required for all new cars and the heat management requirements for these cars are different. The ways in which car manufacturers are taking this issue are also different.

Bachelor's Thesis goals:

Analysis of the heat management approach for cars with different levels of electrification
Cooling requirements, cooling specifics of the car
View on the future

Recommended bibliography:

STONE, Richard. Introduction to internal combustion engines. 3rd edition. Warrendale, Pa.: Society of Automotive Engineers, 1999. 641 s. ISBN 0768004950.

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ABSTRACT

This bachelor's thesis aims to present the thermal management of electric vehicles. It describes the basic principles and requirements of the individual thermal components. In the final part, the designs of the systems used by the current vehicle manufacturers are analyzed and compared.

KEYWORDS

Thermal management, EV, PHEV, FCEL, heat pump, BTMS, EV cooling, EV heating, Tesla

ABSTRAKT

Tato bakalářská práce se zabývá tepelným managementem elektrických vozidel. Jsou zde popsány funkce jednotlivých tepelných komponent a nároky na ně kladené. V poslední části jsou rozebrány a porovnány koncepce systémů používaných výrobci současných vozidel.

KLÍČOVÁ SLOVA

Tepelný management, EV, PHEV, FCEL, tepelné čerpadlo, BTMS, chlazení elektromobilu, vytápění elektromobilu, Tesla

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AFFIDAVIT

I declare that this bachelor's thesis is my original work, created under the supervision of Ing. Jiří Bazala and using the literature listed in sources at the end of this thesis.

In Brno 26th May 2023

.....

David Doležal



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INTRODUCTION

These times bring great transport revolution. Fossil fuels, which have powered not only cars parked in our garages but essentially our entire society for more than 100 years, must be limited. The reason is climate change, which, according to studies, is the effect of the production of carbon dioxide. A significant part of this production is created by the burning of fossil fuels. Their production of air pollutants, especially in large cities, is also a big problem. The limitation of combustion engines powered by fossil fuels is no longer just a hypothetical vision for the future, but a real problem, its seriousness is confirmed by decisions from the highest political positions and specifically the restriction of sales of new passenger vehicles with combustion engines from 2035 in EU countries.

The solution is supposed to be a transition to vehicles with alternative drives, especially electric vehicles. Unfortunately, this solution still has a lot of disadvantages, most of them are associated with batteries in the case of battery vehicles, namely maximum range, battery degradation, fast charging and safety. All these factors are related to the thermal management system.

In the case of vehicles with internal combustion engines, the situation was relatively simple, due to low efficiency, a large amount of waste heat was generated, which was either used to heat the cabin or was transferred to the surroundings. In the case of electric vehicles, however, it is more complicated, there are several components inside that require specific thermal management. And not only in the sense of heating or cooling but also in transfer to other components due to increasing overall vehicle efficiency.

Vehicle manufacturers started using these complex systems in recent years, so the problematics is very actual. In the first part of this thesis, there will be analysed requirements for individual components. Next, different solutions of thermal management used in vehicle manufacturers will be compared, because there are many solutions and each of them brings its advantages and disadvantages.

1 ELECTRIC VEHICLE

An electric vehicle (EV) is a vehicle that uses for propulsion an electric motor instead of an internal combustion engine [1].

This technology is nothing new, interest in electric vehicles has already risen around the 1900s, at that time there were even more electric vehicles than combustion engine ones. Around 1920, however, interest in EVs decreased due to very short ranges and top speeds. The complete decline of interest occurred at the moment when Henry Ford began to mass-produce the Ford Model T vehicle, which was in every way better and cheaper than EVs. Interest in them began to rise with the oil crisis in the 1970s when the availability and price of oil made transport around the world uncertain [1].

However, the proportion of EVs was still almost zero. The arrival of the hybrid electric car Toyota Prius, which was introduced in 1997 in Japan, can be considered the first major milestone. Another very important moment in history occurred around 2008 with the arrival of the Tesla car company and its model Tesla Roadster, which was a luxury electric sports car, which could go more than 320 km on a single charge. Even other car manufacturers were not left behind, in 2010 Nissan came with the popular model Leaf and then Chevrolet with the first mass-produced plug-in hybrid - the Volt model [1], [2]. In the following section, the types of electric vehicles will be described.

Battery Electric Vehicle (BEV)

These vehicles use one or more electric motors for propulsion and the energy is stored in the battery. They do not contain an internal combustion engine, so they are very quiet, the only sound produced is air and tire resistance. Their range is approximately about 150-700 km [3]. The battery must be charged from an external source, which is also the biggest weakness of these cars. Even if manufacturers try to speed up the charging process, for example by using more powerful chargers, charging is still incomparably slower compared to refuelling. The advantage is the high efficiency of the car [1].

Hybrid Vehicle (HEV)

Hybrid vehicles are powered by a combination of an internal combustion engine and an electric motor. This is their advantage, namely the possibility of storing energy in the fuel and at the same time using the high efficiency associated with the electric drive, which is mainly used at lower speeds, for example in cities [1]. Hybrid vehicles can be divided:

According to the arrangement of the drive train:

- Series hybrid
- Parallel hybrid
- Series-Parallel hybrid

According to the degree of hybridization:

- Mild hybrid
- Full hybrid
- Plug-in hybrid

Serial Hybrid

They can also be named extended-range electric vehicles (EREVs) or range-extended electric vehicles (REEVs). They are similar in concept to BEVs, energy is stored in a battery and the wheels are driven by an electric motor. However, there is also an internal combustion engine that serves purely for the production of electrical energy, which is then used to drive the electric motor or recharge the battery. In the case when it is necessary to use the maximum mechanical power, the electric motor is powered by both the battery and the internal combustion engine [4].

Parallel Hybrid

In the case of this design, the electric motor and the internal combustion engine are connected in parallel, one or both of them can be used to drive the wheels. The switching of these drives depends on their operating conditions in order to achieve maximum efficiency. When power demands are low, the internal combustion engine can be used as a generator to charge the battery [5].

Series-Parallel Hybrid

It combines serial and parallel design. This is the most advanced and complex system, there are many modes for propulsion. Both engine and electric motor can work independently of each other [5].

Mild Hybrid (MHEV)

The vehicle includes an electric motor, but primarily uses an internal combustion engine for propulsion. The electric motor does not have enough power to propel the vehicle on its own, it only helps when the internal combustion engine is not efficient, such as during starts and sharp accelerations. It is usually supplemented with an accumulator that stores energy from recuperation [5].

Full Hybrid (FHEV)

These vehicles are capable of fully independent electric drive. Their battery already has enough capacity to be able to store energy for a few tens of kilometres of driving. The disadvantage is higher technical complexity [5].

Plug-in Hybrid (PHEV)

It is a full hybrid, which is additionally supplemented with elements that allow the battery to be recharged with external sources [5].

Fuel Cell Vehicle (FCEV)

The concept is very similar to battery vehicles, they even include an accumulator, but the primary energy storage is hydrogen, which is stored inside the fuel tank. The chemical reaction of hydrogen and oxygen from the surrounding air in the fuel cell stack creates electrical energy, which then travels to the battery. From this energy is a powered electric motor, which drives the wheels. [6].

2 THERMAL REQUIREMENTS

2.1 THERMAL COMFORT IN VEHICLE

Thermal comfort is defined as “that state of mind which expresses satisfaction with thermal environment”. The ideal temperature of the human body is within range 36,5-36,9°C. The body is able to produce more heat using basal metabolism or decrease using perspiration. If external conditions and heat generated by basal metabolism are balanced, then microclimate is ideal. Maintaining this microclimate is necessary not only for comfort but mainly for active safety, because the wrong microclimate causes deterioration of the driver’s attention, in extreme cases it can endanger health [7], [8]. Recommended values of microclimate in car cabin are:

- Air temperature 18-22°C
- Relative humidity 40-60%
- Air flow speed 0,1 m/s at 18°C and 0,4 m/s at 23°C
- Air exchange 25 – 50 m^3/h of fresh air
- Concentration of pollutants 0-17% CO_2 , 0-0,01% CO, 0-1 mg/m^3 of dust [8]

The car’s cabin space has a relatively small volume and weak thermal insulation, which means the inner microclimate is highly affected by external conditions. Among these factors we can include:

- Weather (temperature, wind conditions, intensity of sun)
- Car construction (size of windows, body colour, used materials in the interior)
- Number of passengers

To maintain an ideal microclimate in a cabin despite external conditions, it must be regulated using cabin heating, air conditioning and ventilation [9].

2.1.1 CABIN HEATING

The purpose is to increase the temperature so that it can reach the ideal microclimate. The heating system must secure internal temperature 18°C during external temperature -15°C for 80% of vehicle’s maximum speed. Applies to vehicles, which maximum speed is above 80 km/h. Hot air should be delivered at legs and shouldn’t at head [8].

Vehicles with internal combustion engines has relatively small brake thermal efficiency (BTE). Modern diesel engines achieve BTE 40-47%, while petrol engines have BTE only about 30-36% [10]. This cause huge heat loses, this waste heat can be easily used for heating the cabin. With EV and PHEV cars it’s difficult. Because it’s powertrain has much higher efficiency, there is only small amount of heat produced in different parts and different conditions. Systems using different ways to use waste heat energy will be described in detail in next chapters [11].

Systems used for heating cabin can be divided as follows:

- PTC heating
- Heat pump

2.1.2 CABIN AIR CONDITIONING

Air conditioning system is device, which is supposed for cooling air and improve microclimate in cabin. In addition, it is reducing air humidity in cabin, which is used for defogging windows and again improving active safety. Air conditioning is included in almost every modern electric car in the form of conventional system powered by electric compressor or as part of heat pump [8].

2.1.3 CABIN VENTILATION

Ventilation system is providing clean air and takes away redundant heat produced by external conditions. To keep fresh air, it is necessary to deliver minimum $45 \text{ m}^3/\text{h}$ of air per each passenger during driving and when the vehicle is stationary. Blowing air should be continuous and should cover whole passenger's body. Air blowing on head, legs and hands shouldn't be too strong, maximum speed is only 0,5 m/s.

Air ventilation system should be over pressured to 30 Pa for preventing penetration exhaust gasses, cold or hot external air.

Concentration of CO must be lower than $300 \text{ mg}/\text{m}^3$, concentration of CO_2 must be lower than 0,5%, which is defined by hygienic standard for 8 hours stay [8].

2.2 BATTERY THERMAL MANAGEMENT

Most modern cars use it to store energy for drive lithium-ion battery. This type is most used due low discharge rate, long life cycle and high energy density.

Li-ion cells include 2 electrodes- cathode, which is made from lithium-based material and anode, which is made from graphite. During charging or discharging battery ions are moving from one electrode to other through substance called electrolyte. During this process is generated electric energy, which is used to drive the vehicle [3].

Battery cells can be in form of cylindrical, prismatic or pouch composition. Many of these cells are placed together and they create a battery module. These battery modules create battery pack. For example, Tesla Model S P85's battery pack contains 16 modules, which are total 7104 cells with marking of 18650 [12].

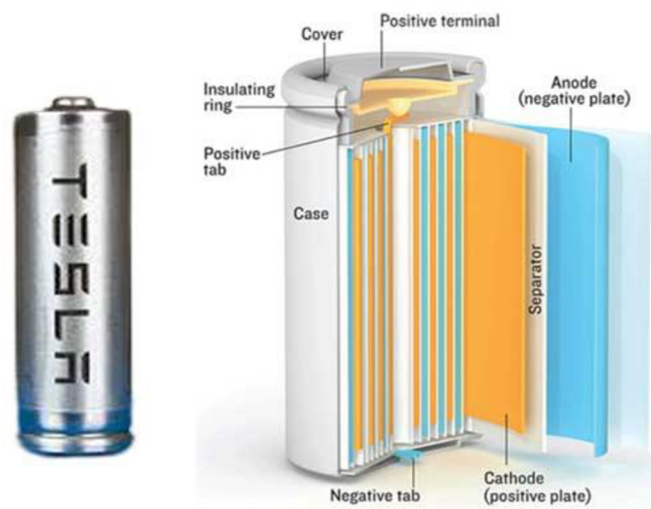


Figure 1. Tesla's battery cell [12]

It is important to mention that, in battery cell is produced heat due to two factors- electrochemical operation and joule heating due to the motion of electrons within battery cells. During traveling, the temperature should be maintained in range 15-35°C [13]. In cold conditions the battery must be heated up after vehicle operation has started. Special condition is charging, temperature is increased for minimalizing losses and keeping charging speed as fast as possible. If the temperature is exceeded, the charging current is reduced. It is very difficult to maintain this temperature, especially during fast charging, because a large amount of heat is generated, which is difficult to efficiently transfer to the surroundings when the vehicle is stationary.

At low temperatures the battery has higher electrical resistance, which decreases power and driving range, moreover there is higher potential for battery damage during charging. The same applies for too high temperatures, in extreme cases of temperatures above 80 °C can cause thermal runaway resulting fire or explosion battery. The system used for regulation is called battery thermal management system (BTMS) and there are 3 types- active, passive and hybrid system [13].

Another big problem is battery degradation. This is a natural process that permanently reduces the amount of energy that the battery can store or deliver. Condition of battery is expressed by a number called state of health (SOH). For example, a new battery with a capacity of 10 kWh has an SOH of 100%. If its SOH drops to 80%, then it behaves as if it had a capacity of 8 kWh. Many factors affect this degradation, such as time, energy cycles, high current draw, state of charge and also temperature. In the figure 2, is shown how the use of better battery thermal management increases the overall life of the battery [14].

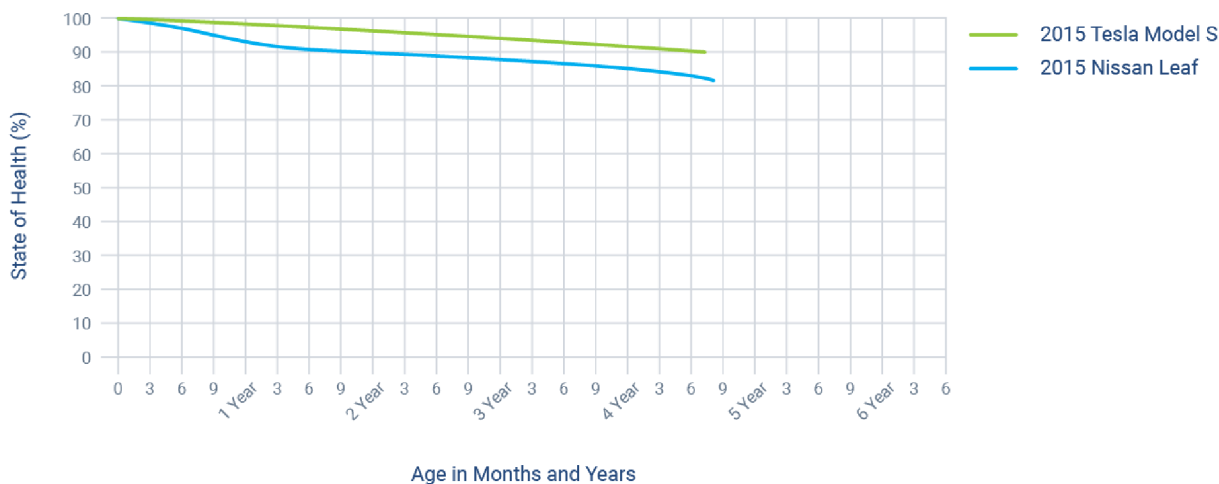


Figure 2. Battery degradation comparison of the 2015 Tesla Model S (liquid cooling) vs. the 2015 Nissan Leaf (passive cooling) [14]

2.2.1 ACTIVE BTMS

Active BTMS uses energy stored in battery for power regulating devices, which forces fluid (air, coolant or refrigerant) into circulation through battery. Fluid ensures heat transfer from/into battery [15].

Forced Air Cooling

It's simple and cheap solution of active BTMS, which has purpose to cool specific overheated parts of battery. For cooling is used fan that blows air through entire battery unit. Cooling power is very low, this type of cooling is being used for example in Volkswagen eGolf , Nissan Leaf or Toyota Prius [15].

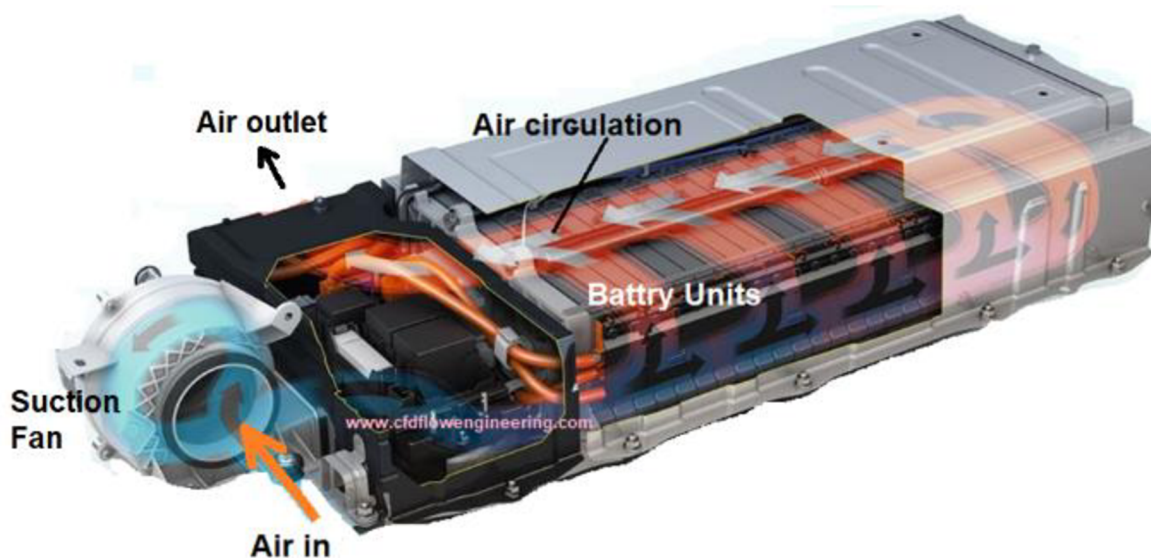


Figure 3. Air cooling system used in Toyota Prius [66]

Coolant Cooling/Heating

This type of active BTMS is most commonly used due to the good cooling performance and convenient design. The coolant which flows through battery, has high heat capacity and convective heat removal rate compared to air. Coolant can be in direct or indirect contact with battery. In the case of direct cooling is used mineral oil which flows directly between cells. Direct cooling provides the best cooling or heating because oil covers entire surface of the cell. Unfortunately, this type of cooling isn't used in mass produced EVs due safety concerns and high cost [15], [16].

Indirect design uses water or glycol-based coolant which flows through piping system between battery modules. Arrangement of battery cells, modules and piping are very important, because battery have to be cooled/heated equally. This type of thermal management will be detailed described in next chapters [16].

Refrigerant Cooling

Refrigerant cooling works on same principle as coolant cooling with one difference- evaporator from air conditioner system is connected directly on battery. This solution brings good heat transfer rate and low space requirements but can't be used for battery heating. This cooling system includes cooling plates, that are connected directly to the refrigerator. This system is being used for example in BMW i3 [15], [16].

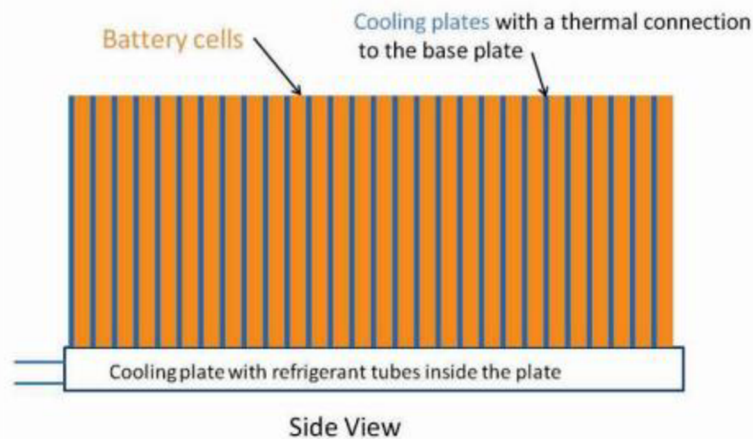


Figure 4. Battery refrigerant cooling [16]

2.2.2 PASSIVE AND HYBRID BTMS

Passive system doesn't need any electrical energy from battery, which improves efficiency of vehicle. To power it only natural sources are used, for example flowing air or gravity. Hybrid system combining 2 or more systems together, typically heat phase changing material or heat pipe with some kind of active cooling system [15].

Passive Air Cooling

It's the simplest and cheapest type of battery cooling. Cold air is being blown through the intakes and flaps brought directly to the battery; heated air is then discharged back into environment [15].

Heat Pipe and Phase Change Material

Both are used only in combination with other systems. Heat pipes are closed tubes, filled with working substance. One side is heated, other one is cooled. Substance starts vaporizing at heated side and moves to side with cooler (tube should be slightly tilted). Cooled fluid starts condensate and returns back to heated side. With this principle, heat can be transferred with very good efficiency even for long distances, which is convenient in modern trend of increasing size of batteries [17].

Phase change materials absorb or release huge amount of heat for period of changing phase. During this process temperature stays at constant value. This material property is advantageous for buffering the BTMS [16].

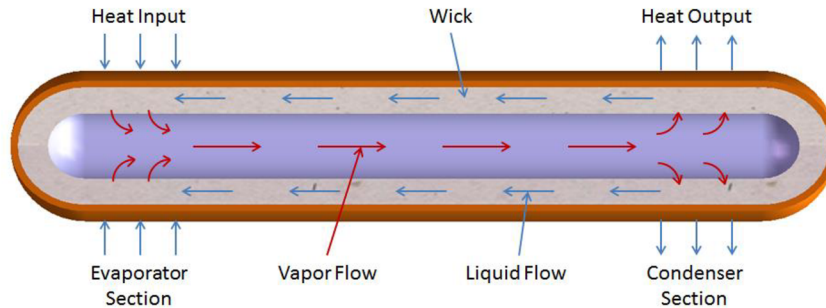


Figure 6. Heat pipe [67]

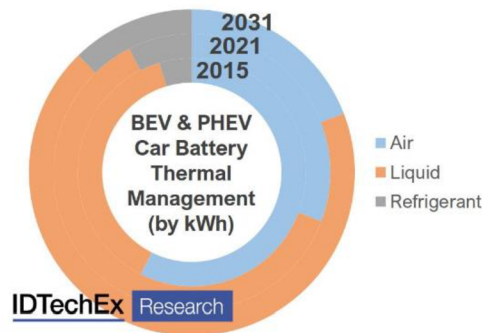


Figure 5. Chart of evolving strategies of EV battery thermal management [68]

2.3 ELECTRIC MOTOR

For drive electric vehicles are used electric motors. It's device, which purpose is transforming electric energy to mechanical energy. Its advantage is simple design, high power compared to size and high torque from zero rpms and ability to recuperation- returning waste energy from braking back into battery. In modern vehicles are used 3 types of motors [18]:

- Permanent-magnet alternating-current synchronous motor (PMAC)
 - Škoda Enyaq iV 60, Honda E, Porsche Taycan, Nissan Leaf, Hyundai Kona, Toyota Prius, Tesla Model 3 and Y (with combination of asynchronous induction motor for AWD powertrain) [3]
- Asynchronous induction motor
 - Audi e-tron S, Mercedes-Benz EQC 400 4Matic [3]
- Externally excited synchronous motor
 - BMW Ix3, Renault Zoe R110 [3]

Next huge advantage of electric motors is high efficiency, which ranging 60-96%, depending on generating torque and speed (figure 7) [19]. Residues are losses in form of heat, which arise in coils due to resistance. In case of bad cooling motor ECU will reduce supplied current to prevent thermal damage of motor. This has unfavourable affect to output power. With usage of good cooling system, the reduction of output power is lower, this is very convenient because it can be achieved same power with less sized and lighter motor. Smaller mass affects total efficiency of vehicle [20].

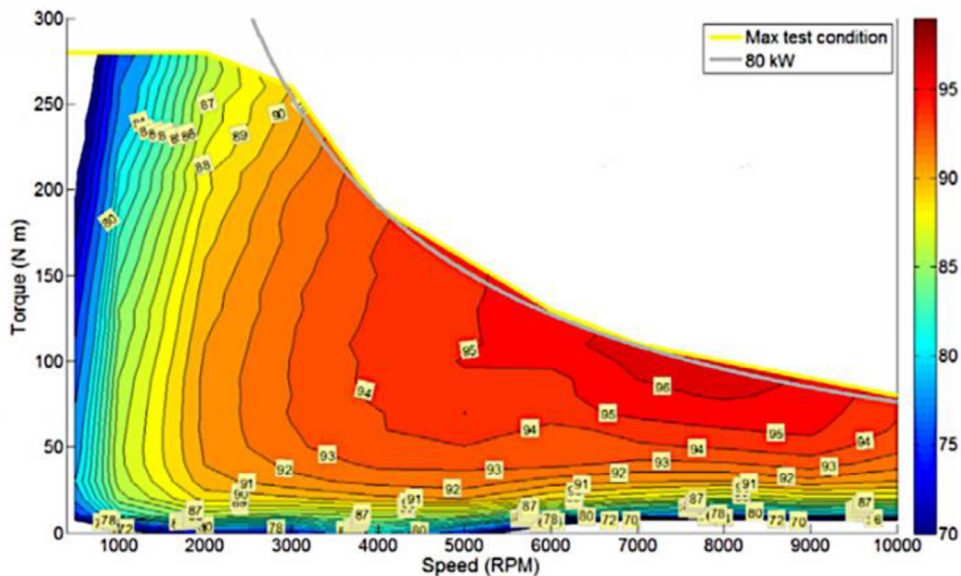


Figure 7. Electric motor efficiency according to produced torque and speed [19]

Electric motors can be cooled by follow ways:

Air Cooling

It's simplest and cheapest cooling system. Electric motor is cooled by outside flowing air or air forced by fan. The usage of this cooling system is rapidly decreasing due low cooling performance [21].

Coolant Cooling

It's often used solution of cooling system. Water-glycol coolant flows in "Jacket" around stator, where is heat taken away into the cooler. Liquid isn't in direct contact with stator of electric motor, so distribution of coolant is more complex. Advantage is high thermal capacity of coolant, so it deals with long lasting thermal loads [20], [21].

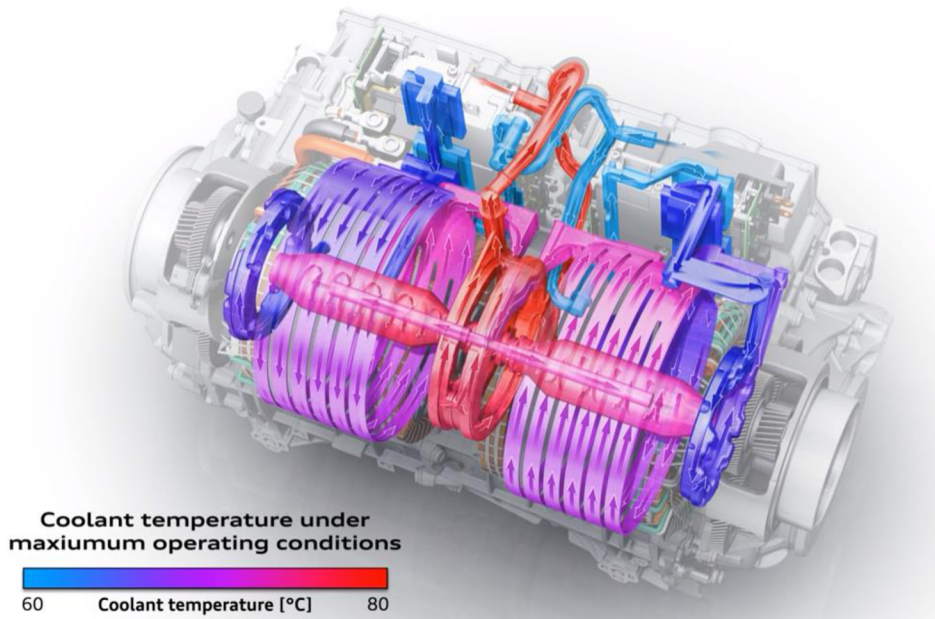


Figure 8. Water cooling of twin motor used by Audi E-Tron [70]

Oil Cooling

The most common electric motor cooling system is oil cooling. Advantage of this system is that oil is in direct contact with motor's internal parts, which means better heat convection, in addition oil is ensuring lubrication of mechanical parts. The heat can be removed via the cooler to the surroundings or can be connected to one of the other water-cooling loops through the heat exchanger [20], [21].

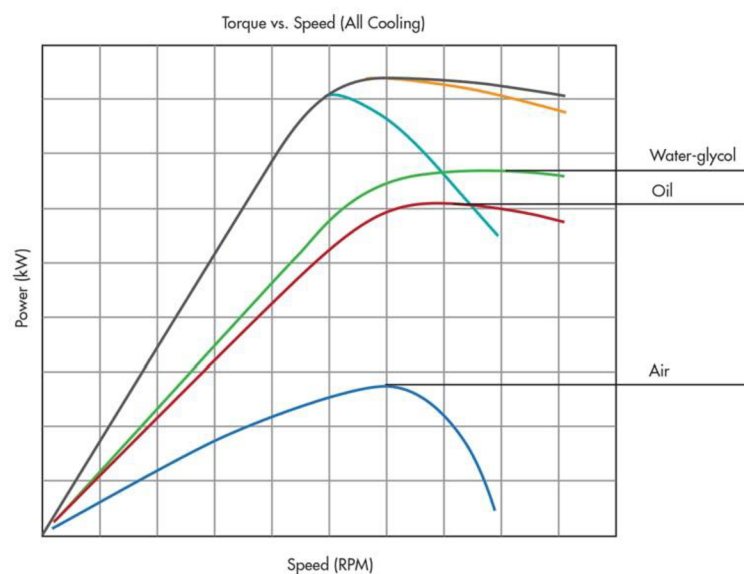


Figure 9. Effect of coolant type on continuous power and and peak power of a PMAC motor [21]

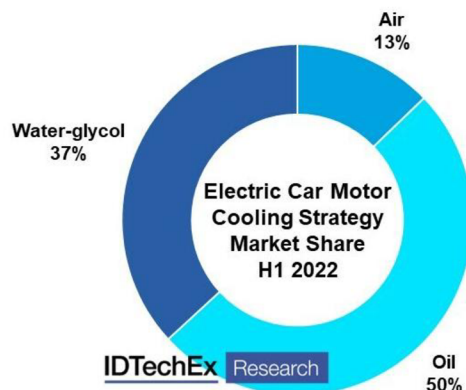


Figure 10. Chart of actual used strategies of EV motor cooling [69]

2.4 INVERTER

As mentioned before, EVs use PMAC, asynchronous and induction motors- all types powered by alternating current. Unfortunately, batteries are dc devices, which means this high direct current must be transformed to alternating current, for this purpose is used inverter. Inverter contains high voltage IGBTs or MOSFETs which using pulse width modulation (PWM) generating 3 sinusoidal currents spaced 120° , which flows directly into motor. It's driven by driver unit, which is giving signals for changing frequency or amplitude of current. With this principle is achieved continuous and precise controlling from zero to hundreds of rpm's. Next purposes of inverter are transforming electricity during charging from grid with alternating current and transforming alternating current to direct current for battery in case of recuperation during braking. During these processes inverter generates a heat, which must be managed, or damage of electronics is possible [22], [23], [24]. Inverter can be actively or passively cooled same as battery. In case of active cooling is the inverter connected to same loop as electric motor, because it has similar operating temperature between $45-60^\circ\text{C}$ [25].

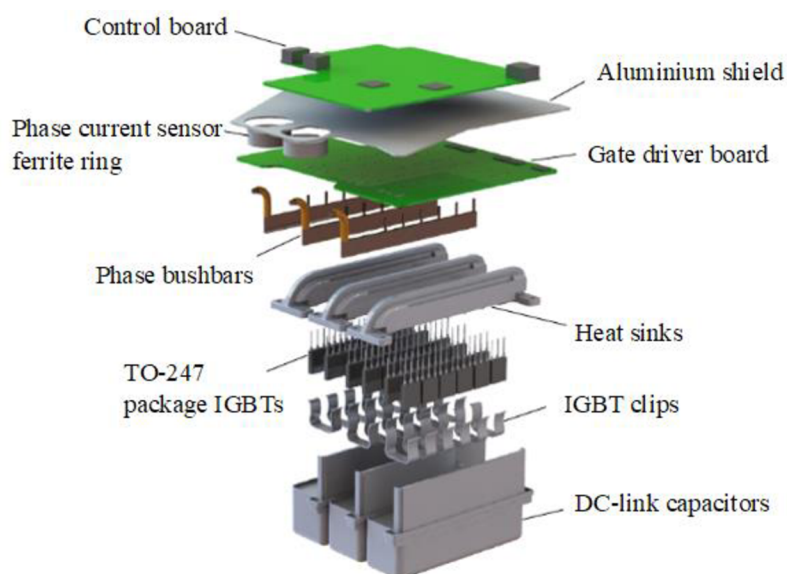


Figure 11. Tesla Model S inverter components [71] (edited)

2.5 INTERNAL COMBUSTION ENGINE

Despite the fact, that cars with internal combustion engines are on the decline today, it still makes sense to deal with their cooling for use in hybrid vehicles. Internal combustion engine is device transforming chemical energy stored in fuel (petrol, diesel, LPG, CNG, ethanol...) to thermal energy, then mechanical energy. During this process is only 30% of heat energy transformed to mechanical energy, 65% are heat losses and 30% of heat is taken away to cooling system [26]. This means, cooling system has huge heat surplus. Part of this energy can be used for heating the cabin, rest is taken away to environment. This is a reason that requires very effective cooling system because at high temperatures the engine could be damaged. Ideal temperature of engine coolant is between 80-95°C, 90-115°C in case of lubricating oil [27].

Ways of cooling:

- Air cooling
 - Forced air cooling
- Coolant cooling
 - Thermosiphon circulation cooling
- Internal cooling
 - Phase changing during evaporating of fuel [28]

Due to bad and uneven cooling effect of air-cooling modern vehicles uses only coolant cooling.

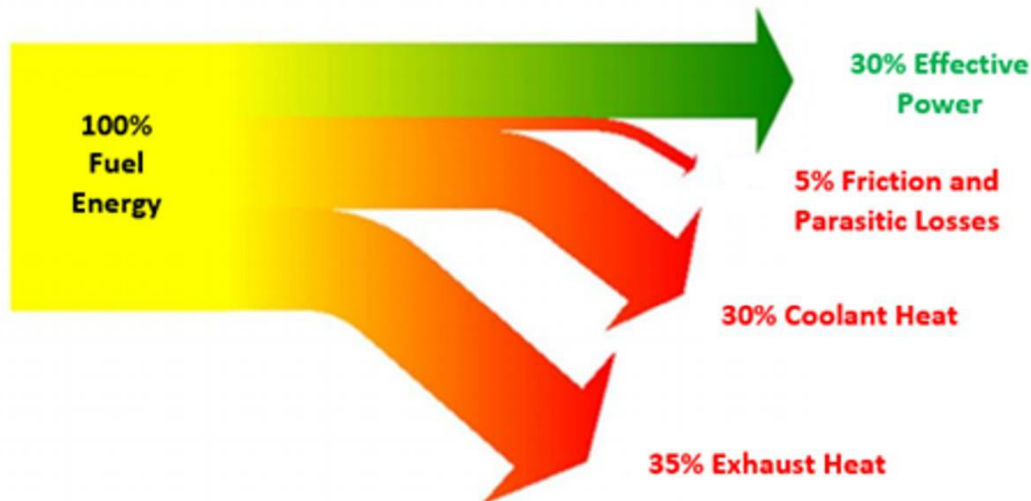


Figure 12. Typical energy split in gasoline internal combustion engine [26]

2.6 FUEL CELL

The development of battery vehicles brings many new challenges. One of the biggest is energy storage and maximum range. Because battery vehicles have a relatively long charging time (even when they are connected to fast charger) and short range, manufactures are trying to come up with alternatives with ecological drivetrains. Probably most discussed is the hydrogen solution.

Hydrogen cars can be divided to two types- with internal combustion engine or fuel cell. Although hydrogen internal combustion has reached several functional prototypes, its future development is highly unlikely due to low efficiency. Vehicles with fuel cells can be a better choice. They still use an electric motor for propulsion, they even include an inverter and a small battery just like battery vehicles. The difference is in the fuel cell, which is an electrochemical device in which the fusion of hydrogen fuel with oxygen produces electricity, heat, and water.

The principle is as follows: Hydrogen is supplied to the anode (negative electrode) and oxygen to the cathode (positive electrode). With the help of a catalyst, the hydrogen at the anode is split into positively charged ions and electrons. Hydrogen ions subsequently travel through the electrolyte and combine with oxygen, water is produced. Electrons also travel to the cathode, passing through the electrical circuit, creating an electric current that is subsequently stored in the battery [29].

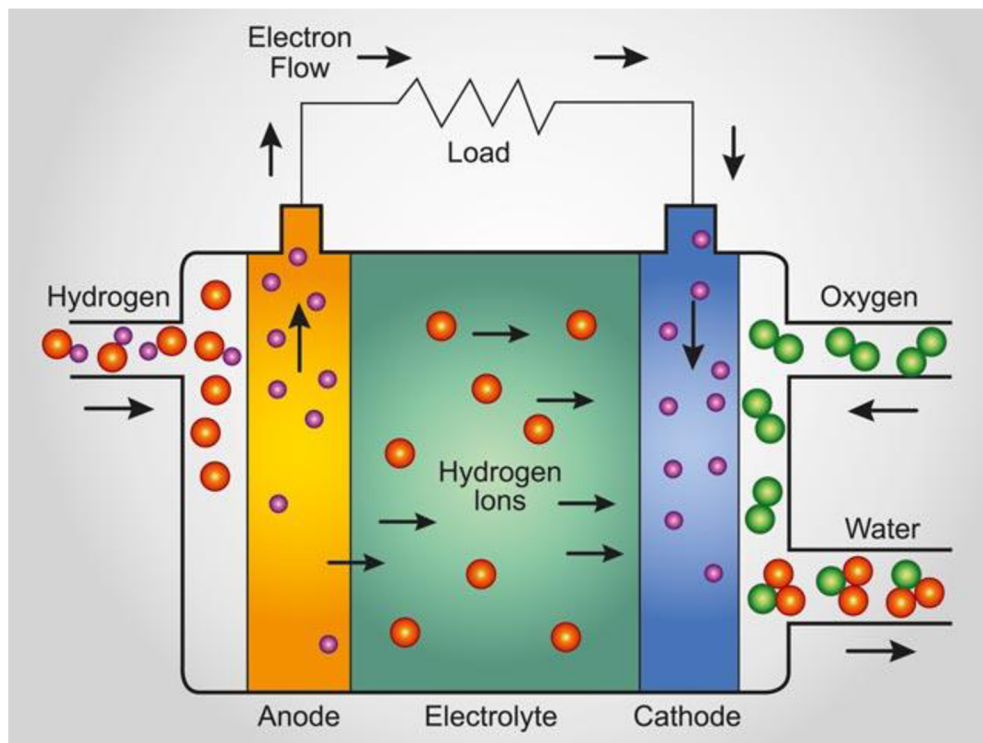


Figure 13. Operating principle of a fuel cell [77]

There are these types of fuel cells:

- Polymer electrolyte membrane fuel cells PEMFC– used in Toyota Mirai
- Direct methanol fuel cells DMFC
- Alkaline fuel cells AFC
- Phosporic acid fuel cells PAFC
- Molten carbonate fuel cells MCFC
- Solid Oxide Fuel cells SOFC [29]

In terms of temperature, fuel cells can be divided into low-temperature and high-temperature ones. In vehicles, we can meet low-temperature fuel cells, their temperatures range between 60-80°C and they have a large heat dissipation, due to a relatively low efficiency ranging between 40-60%. On the other hand, it is also necessary to heat the fuel cells, because at low temperatures the fuel cell does not provide the necessary power and has a slow start-up [29], [30]. At the moment, only liquid active cooling of fuel cells is used in cars [31].

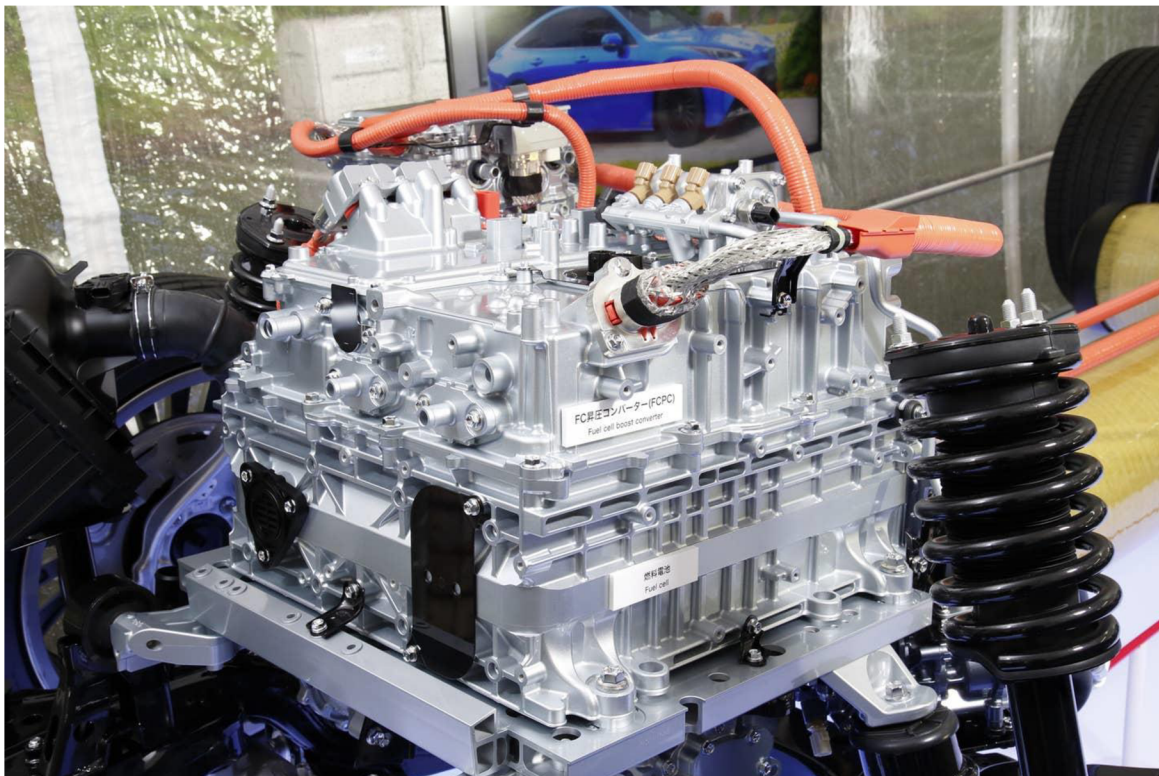


Figure 14. Toyota Mirai fuel cell [72]

3 THERMAL COMPONENTS

3.1 PTC HEATER

As already mentioned, electric vehicles without an internal combustion engine require specific heating systems. PTC or Positive Temperature Coefficient heater is very simple and reliable device used in almost all electric vehicles. Includes PTC thermistor which is semiconductor resistor. This element is used for heating. With increasing temperature resistance increase too. PTC heaters have advantages of low thermal resistance and high heat exchange [32], [33].

These devices can work in two designs:

- Air heating
- Water heating

Air Heating

This type is used primary for cabin heating or windshield defogging. It's not very popular because low voltage power supply is used, therefore the PTC heater has low output power, and it can't be used for heating a battery. On the other hand, it's inexpensive and easy for cockpit temperature controlling [33].

Water Heating

This is most common type of heating. It can be used for heat whole circuits with battery, cabin and engine. It's very effective and has high output power. This solution has disadvantages too- it's more expensive and harder to control cockpit heat [33].

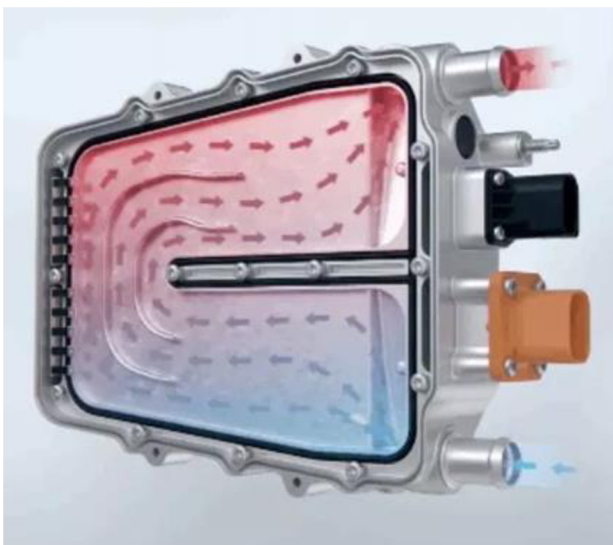


Figure 16. PTC coolant heater [33]



Figure 15. PTC air heater used by Tesla Model 3 [73]

3.2 HEAT PUMP AND AIR CONDITIONER

A heat pump is a device that works on the basis of the inverted Carnot cycle, which allows energy to be pumped from low temperature environment (outdoor environment) to a higher temperature environment (cabin, battery). Thanks to this, the system (cabin, battery) is being supplied more heat than it takes from the energy source (battery), which has a positive effect on the range of the electric vehicle [34], [35].

By modifying the design, the heat pump can be converted into an air conditioner - the compressor moves heat from an environment with a lower temperature (cabin) to an environment with a higher temperature (outdoor environment). In theory, it is enough to just turn the direction of the refrigerant flow, in practice a more complex design is required, the refrigerant does not flow in the opposite direction here but is directed to other circuits using electronic valves [34], [35].

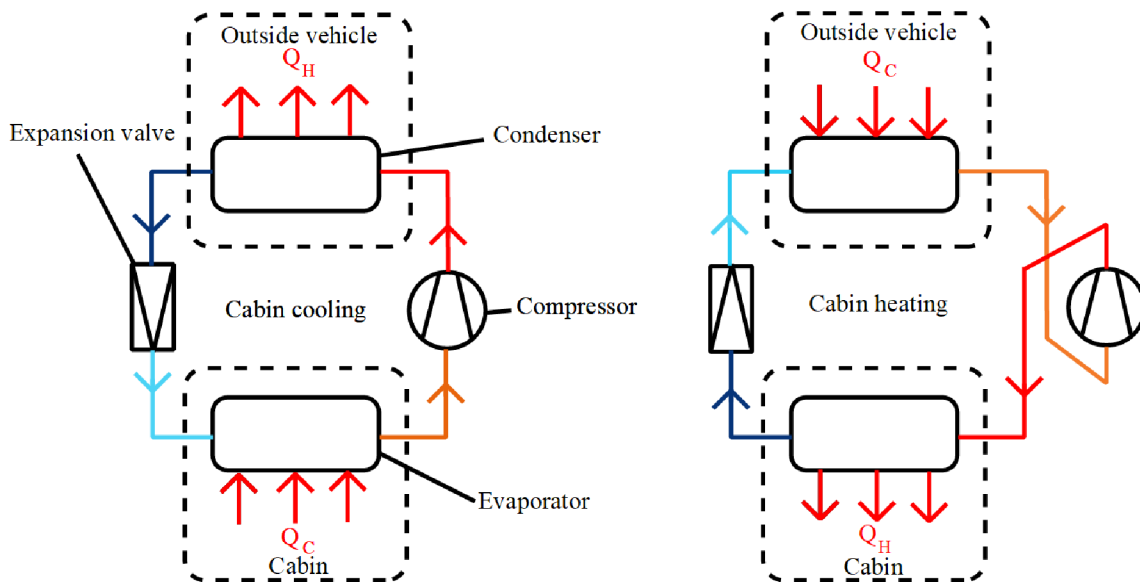


Figure 17. Air conditioner and heat pump principle

The principle is as follows. A compressor driven by an electric or combustion engine or electric motor compresses the medium (2), the temperature rises. The medium then travels to the condenser, where it transfers heat (cabin, battery), while its temperature drops and condenses (3). Subsequently, the medium travels to the expansion valve, where the pressure drops sharply (4), it takes the ambient heat energy in the evaporator and evaporates (1). The medium travels to the compressor again and the whole cycle repeats [34], [35].

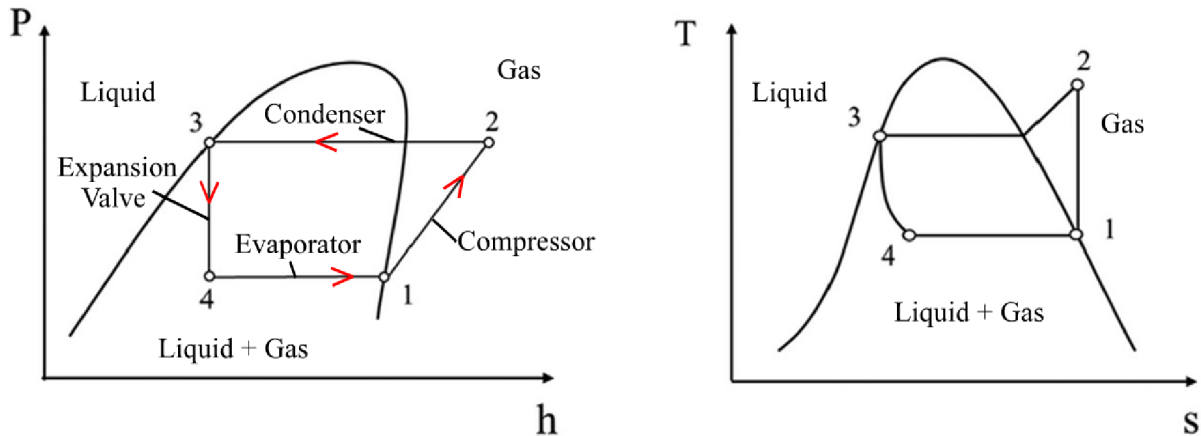


Figure 18. P-h and T-s diagrams of heat pump cycle [74] (edited)

Efficiency of heat pump is described by COP (Coefficient of Performance). The following applies to the heat pump:

$$COP_H = \frac{|q_H|}{|a_0|} = \frac{|q_H|}{|q_H| - q_C} = \frac{h_2 - h_3}{(h_2 - h_3) - (h_1 - h_3)} = \frac{h_2 - h_3}{h_2 - h_1}$$

For air conditioner:

$$COP_C = \frac{|q_C|}{|a_0|} = \frac{|q_C|}{|q_H| - q_C} = \frac{h_1 - h_3}{(h_2 - h_3) - (h_1 - h_3)} = \frac{h_1 - h_3}{h_2 - h_1} \quad [34]$$

While the COP of a PTC heater is about 1, because it creates only as much heat as electric power is supplied to the input, the COP of a heat pump is 1-4, which depends on the ambient temperature. When the temperature decreases, the COP also decreases.

Using a heat pump is a very good way to increase range in cold conditions. This is also used by car manufacturers, the number of cars that are using it is increasing. Research, which was conducted on 13 popular BEVs, confirmed the advantages of the heat pump, where it can be observed that cars using heat pumps have noticeably lower range losses in cold conditions [36].

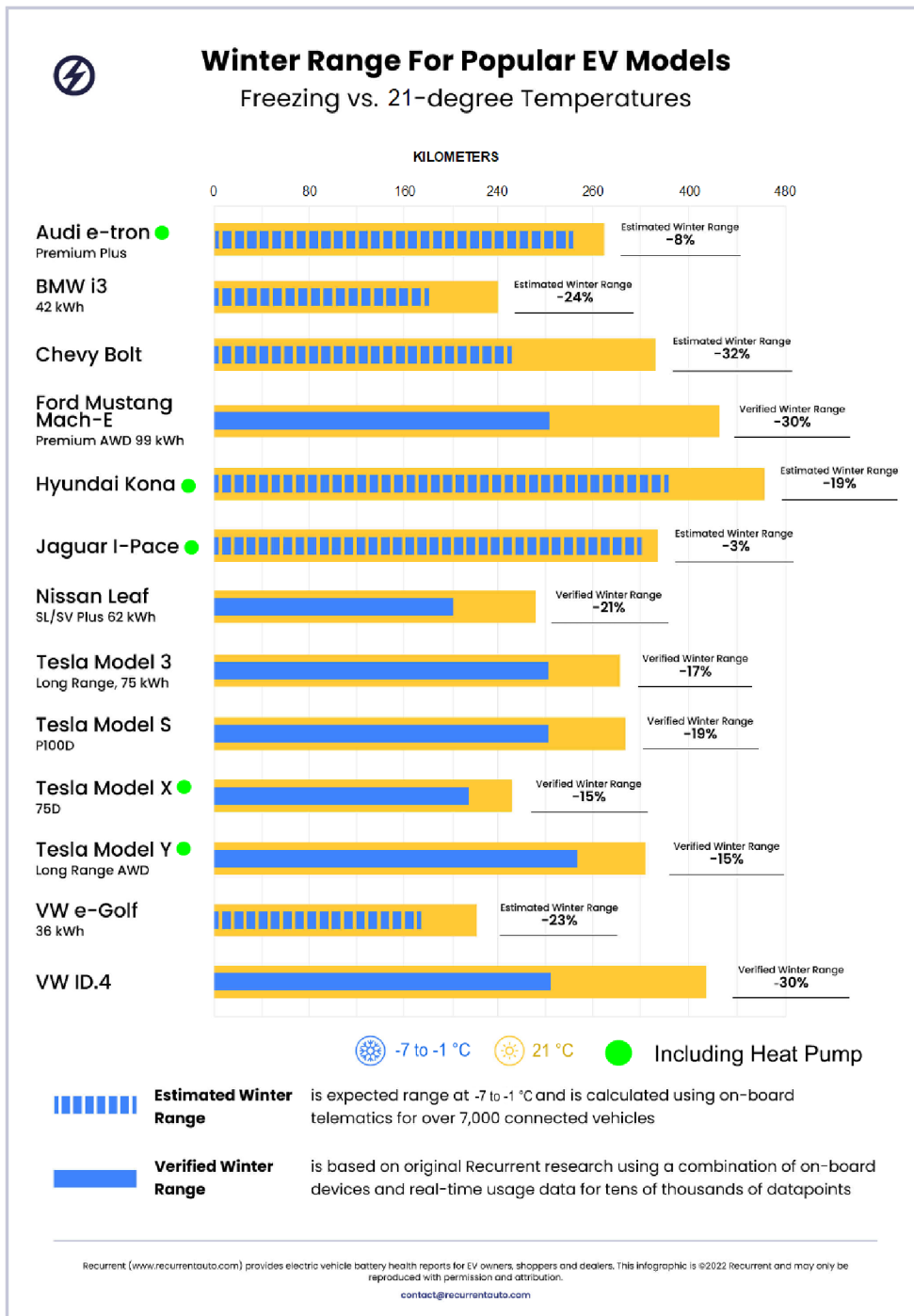


Figure 19. Research of impact of cold weather to EV's range [36] (edited)

The only disadvantage of heat pump can be higher complexity and higher price. However, compared to the price of the vehicle, it is not a particularly expensive item. Skoda, Audi or Hyundai offer heat pump for about 30 000 Kč. It is common that heat pump is a part of standard equipment for example in Tesla Model Y [3].

3.3 HEAT EXCHANGER

The heat exchanger is a device designed to transfer heat from one fluid to another. Every modern electric vehicle and vehicle with internal combustion engine contains several types of these exchanger, and this number is increasing due to growing environmental and passenger comfort requirements. Along with the development of heat exchangers, the requirements for them grow as well - weight reduction, thermal efficiency, new designs and materials that will be more corrosion resistant [37]. We can divide them according to the method of heat transfer:

- Water-Air
- Air-Air
- Refrigerant-Air
- Oil-Air
- Refrigerant-Water

3.3.1 WATER/AIR/REFRIGERANT/OIL – AIR HEAT EXCHANGER

In this case, the coolant can be any liquid or gas medium, the heat is then removed to the surroundings. In the vehicle, we can find it in the form of:

- Radiator (Water-Air)
- Condenser (Refrigerant-air)
- Evaporator (Refrigerant-air)
- Heater (Water-Air)
- Intercooler (Air-Air)
- Oil cooler (Oil-Air)

Radiator

Purpose is to remove the heat from the motor received by the liquid to the surrounding environment. In the case of cars with an automatic transmission, the radiator may also include an oil cooler. The principle of operation is the same as for other air-based heat exchangers. Radiator includes two tanks, coolant enters the inlet, then is forced by pump across core which is made of round or oval-shaped core tubes joined with cooling fins. Those fins are exposed to air flowing through the radiator. Due to large area of cooling surface heat is effectively taken away. Cooled fluid exits the outlet tank and returns back to the motor [38].

There are two designs - downflow and crossflow radiators. In case of downflow radiator tanks are vertical and core is horizontal while crossflow radiators have vertical tanks and horizontal core. Most modern vehicles use crossflow radiators due to several advantages: more heat is removed thanks to larger core area, fluid flows slower across the core, coolant makes multiple passes through the core. They have convenient proportions too, because they have smaller height and larger length which corresponds with grille shape [38], [39].

The tanks are made from nylon-reinforced plastic, the core is from aluminium. These materials are corrosion resistant, are easily formed and have good heat transferability [38].

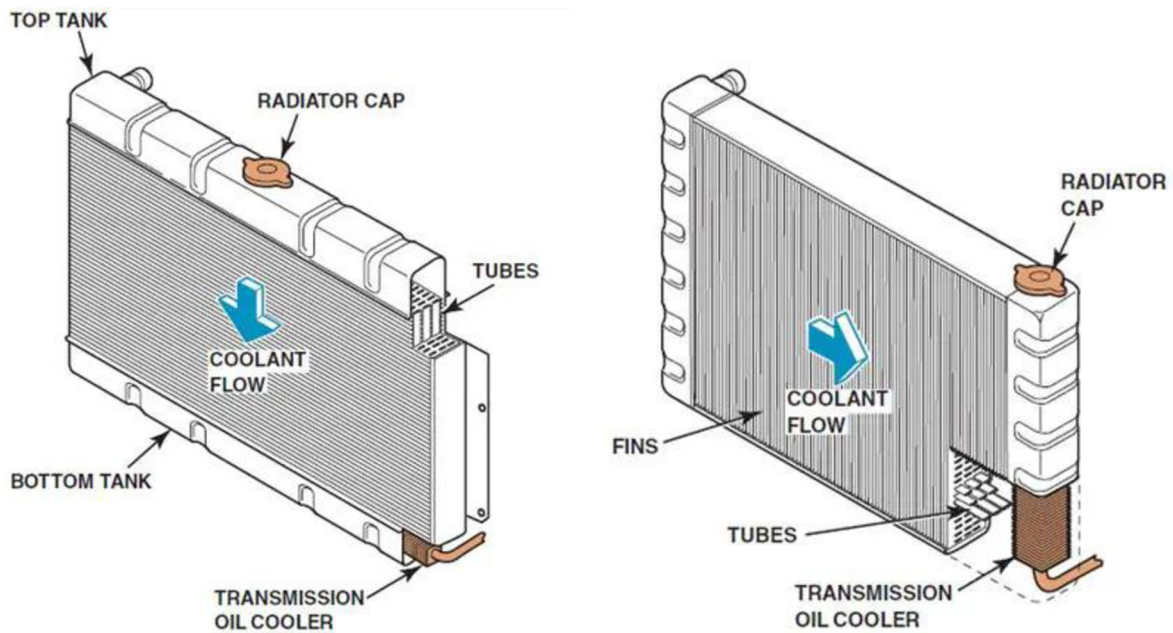


Figure 20. Designs of down-flow and cross-flow radiators [38]

Condenser

Condenser is part of air conditioner or heat pump. It can be located in the front grille of the vehicle to remove heat from the vehicle or in the dashboard in the case of a heat pump system to heat the cabin. Its task is to remove heat from the refrigerant. High-pressure, high-temperature gas refrigerant is sent from the compressor then condenses here into liquid refrigerant and emits heat absorbed by the evaporator. The most common design is a parallel flow condenser with extruded multiport tubes [37].

Evaporator

Just as the condenser is part of the air conditioner and heat pump, the design is again similar to the radiator and condenser. Evaporation of the refrigerant occurs here as a result of receiving ambient heat. In addition, its function is to dry the air for defogging [37].

Heater

The heater transfers the heat received from the engine or other parts to the vehicle cabin. The construction is again similar to that of the radiator [37].

Oil cooler

Oil applied for lubrication plays a significant role. In order for the oil to function properly and not degrade quickly, it must be maintained at an optimal temperature. Especially diesel engines, automatic transmissions and electric motors require advanced requirements for oil cooling, which is achieved with the help of a cooler. They exist in two variants - air-cooled and water-cooled. In the case of air-cooled ones, the construction is the same as for other air-cooled variants. Water-cooled ones will be described in the chapter [37], [38].

3.3.2 OIL/REFRIGERANT-WATER HEAT EXCHANGER

There are cases when air cooling is not suitable, or when we only need to transfer the heat to another part of the system. For these cases, a plate heat exchanger or a tubular heat exchanger can be used, whose working medium can be oil or refrigerant in combination with water. In the case of oil, it is for cooling an internal combustion engine or an electric motor, on the other hand, refrigerant is used to cool the cooling loop with water.

Plate heat exchanger consists of several plates with multiple channels for liquid to flow through. Coolant flows through one set of channels while the oil or refrigerant flows through another set of channels. The advantage of this solution is high heat transfer efficiency on small dimensions, because plates create very large surface area. They have lower pressure drop compared to tubular design too [40].

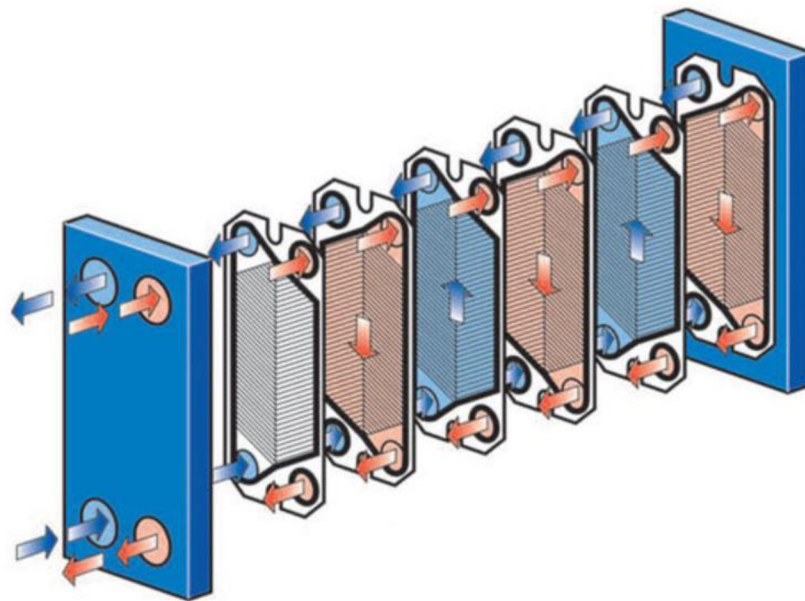


Figure 21. Plate heat exchanger [75]

Tubular heat exchanger is the simplest solution and can be used for cooling oil directly in radiator (figure 20)

4 THERMAL MANAGEMENT DESIGNS

In previous chapters, individual components and requirements for their thermal management were described in detail. For completeness, they are summarized in Table 1.

Table 1. Comparison of operating temperatures and efficiencies of components

	Operating temperature	Efficiency
Cabin	18-22 °C	
Battery	15-35 °C	95%
Electric motor	60 °C	60-96%
Inverter	45-60 °C	95%
Fuel cell	67-77 °C	40-60%
ICE	80-95 °C	28%

Each component has different requirements in terms of operating temperatures. The amount of heat generated is also different, which is approximately equal to the losses. However, the problem is that each component requires different thermal management depending on different conditions.

By these conditions we mean, for example:

- Ambient temperature
- Charging
- Vehicle load
- Vehicle movement

As an example, consider a situation where a battery electric vehicle drives in slightly cold weather and uses high power. At that moment, the battery and the motor produce heat, so it is necessary to cool them. However, since the motor has different cooling requirements than the batteries, it is therefore not possible to connect them to a single cooling circuit. On the contrary, the cabin must be heated due to the ambient temperature.

There are several options for solving this problem, so in the following chapters, the concepts of solutions used directly by current car manufacturers will be discussed.

4.1 BATTERY ELECTRIC VEHICLES

First analysed will be most interesting category and that is the battery electric vehicle. All these vehicles contain a battery, inverter and electric motor. As already mentioned, these components and low heat losses, which are not enough to heat the cabin. Over time, the strategies require thermal management, all have high efficiency in the solutions go through significant evolution. It could be divided into the following concepts.

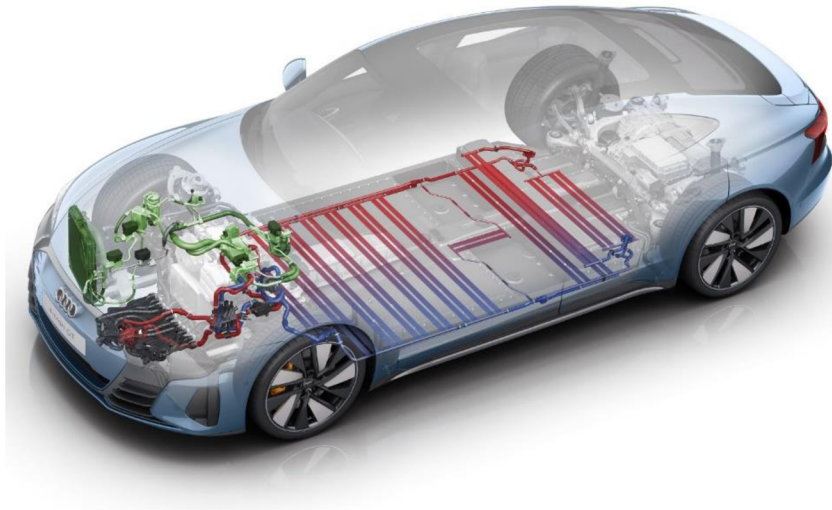


Figure 22. Audi e-tron thermal management layout [76]

4.1.1 CONCEPT 1

4.1.1.1 NISSAN LEAF

It can't be started otherwise than with the Nissan Leaf. This vehicle came on the market in 2010 and for many years held the position of the best-selling battery electric vehicle in the world. Car contained a Li-Ion battery with a capacity of 24 kWh, which was enough for range about 145 km. The drive was provided by a PMAC electric motor with an output of 80 kW [41].



Figure 23. Nissan Leaf [41]

This vehicle comes with very simple thermal management system, which includes 3 loops:

1. Power electronics and motor cooling loop (red line)
2. Cabin heating loop (purple line)
3. Cabin air conditioning loop (blue line) [42], [43], [44]

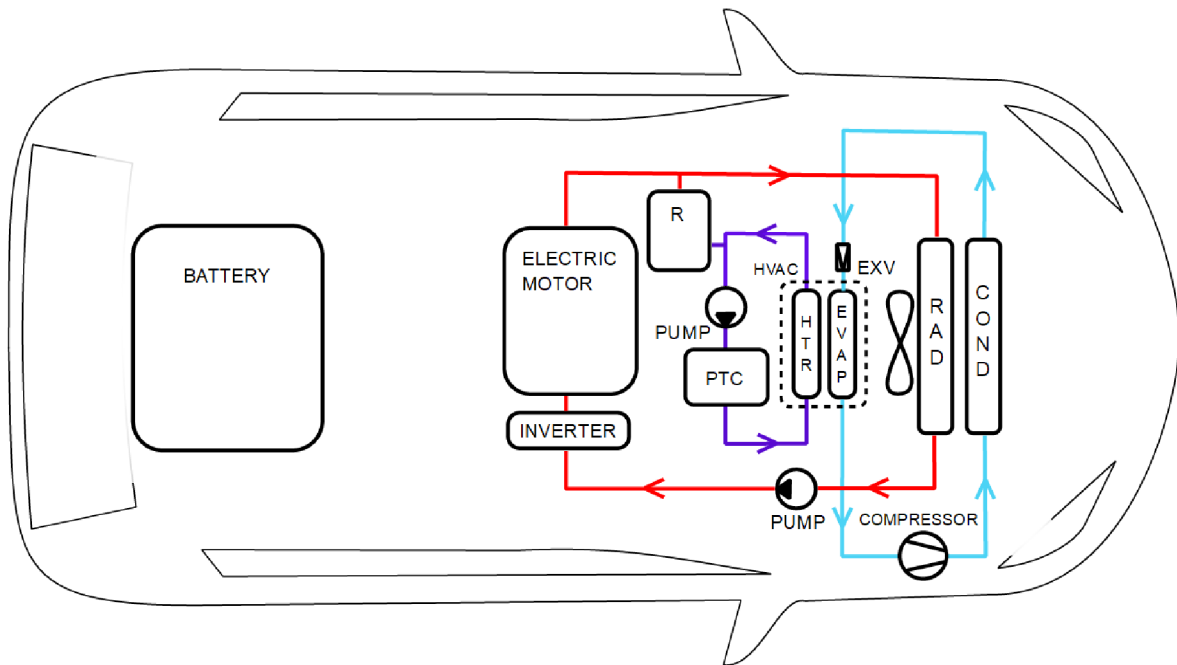


Figure 24. Nissan Leaf thermal management design. R- reservoir, EXV- Expansion Valve, HVAC- Heating, Ventilation and Air Conditioning, HTR- cabin heater, PTC- Positive Temperature Coefficient heater, RAD- Radiator, COND- Condenser, EVAP- Evaporator

In this system, the motor and inverter are cooled by water-based coolant, which circulates using the electric pump. Heat is removed in main radiator and is not used in any way [44].

The cabin is heated by separated loop using a 5 kW PTC heater, which includes a separate pump. The last loop is air-conditioning, its design is identical to conventional vehicles with an internal combustion engine. An interesting fact is that the Nissan Leaf in 2012 was the first to come with a heat pump, but it was a simple type that only used heat from the surrounding environment [42], [43].

The biggest weakness of this car is the absence of BTMS, which, especially in bad weather conditions, causes problems associated with battery degradation and reduced range [14].

4.1.2 CONCEPT 2

The majority of current battery electric vehicles use thermal management to regulate the temperatures of the inverter, motor and battery. It can be realised using 3 circuits (4 in the case of a separate circuit for heating)

1. Power Electronics and motor cooling loop (red line)
2. Battery heating/cooling loop (purple line)
3. Cabin air conditioning loop (blue line)
4. (Cabin heating loop)

4.1.2.1 HYUNDAI KONA (WITHOUT HEAT PUMP)

This vehicle went on sale in 2019. In its more powerful performance version, the vehicle has a Li-Pol battery with a capacity of 64 kWh, an electric motor with an output of 150 kW and 395 Nm of torque. The indicated range is 395 km. As we can see, the parameters against the first-generation Nissan Leaf have improved considerably [45].

Second concept will be explained on this vehicle, because it has the thermal management typical for most electric vehicles. This vehicle uses exactly 3 circuits, which can be operated in 3 modes, depending on the temperature. They are controlled by two 3WV on the cooling circuit and two 2WV on the air conditioning loop [46].

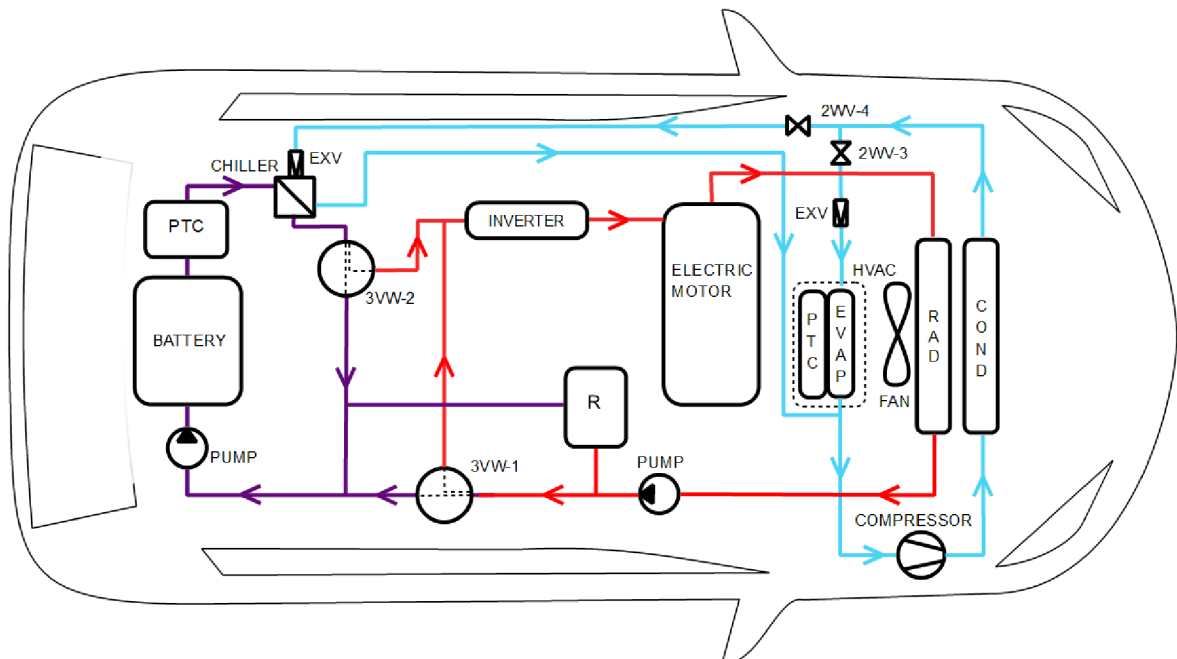


Figure 25. Hyundai Kona thermal management design (no heat pump). 2WV-1 2-way valve number 1, 3WV-1 3-way valve number 1

Mode 1 - Cool Condition

If the outside temperature is in the range of 0-20 °C, the mode for cool condition is activated. In that case, the circuits for the battery and for the motor are connected by two valves (3WV-1 and 3WV-2). Waste heat from the motor and inverter is used for heating the battery. After heating, the battery is kept at an optimal temperature by regulation of a radiator and a fan [46].

Mode 2 - Hot Condition

If the temperature of the cooling liquid rises so much that the radiator is no longer able to cool it enough to keep the battery temperature at the optimal temperature, the valves will turn one complete circuit into 2 separate ones. At that moment, the inverter and motor is further cooled by a radiator and a fan, but the battery on a separate circuit is at that moment only cooled by a “chiller” which is name for plate heat exchanger. It is connected to the air conditioning circuit, which is also used for cabin cooling. Note that each circuit contains its own pump, so separation does not stop coolant recirculation [46].

Mode 3 – Cold Condition

When the outside temperatures are too low (below 0 °C), the system switches to mode 3. It is the same as in the case of mode 2, with the only difference that it is not cooled using a heat exchanger but heated using a PTC heater. Separation of the battery circuit that is very important in this case, because heat is effectively used only for heating the battery [46].

4.1.2.2 TESLA MODEL 3

As already mentioned, this system is used by most modern battery electric vehicles such as the Porsche Taycan, Audi RS e-tron GT, fiat 500e (here only the Battery cooling loop is fully separated and does not use waste heat from the electric motor) or the currently best-selling battery electric vehicle in the world - Tesla Model 3 [47], [48], [49], [50]. This vehicle also contains 3 circuits, it also shows one interesting trend - modularization.

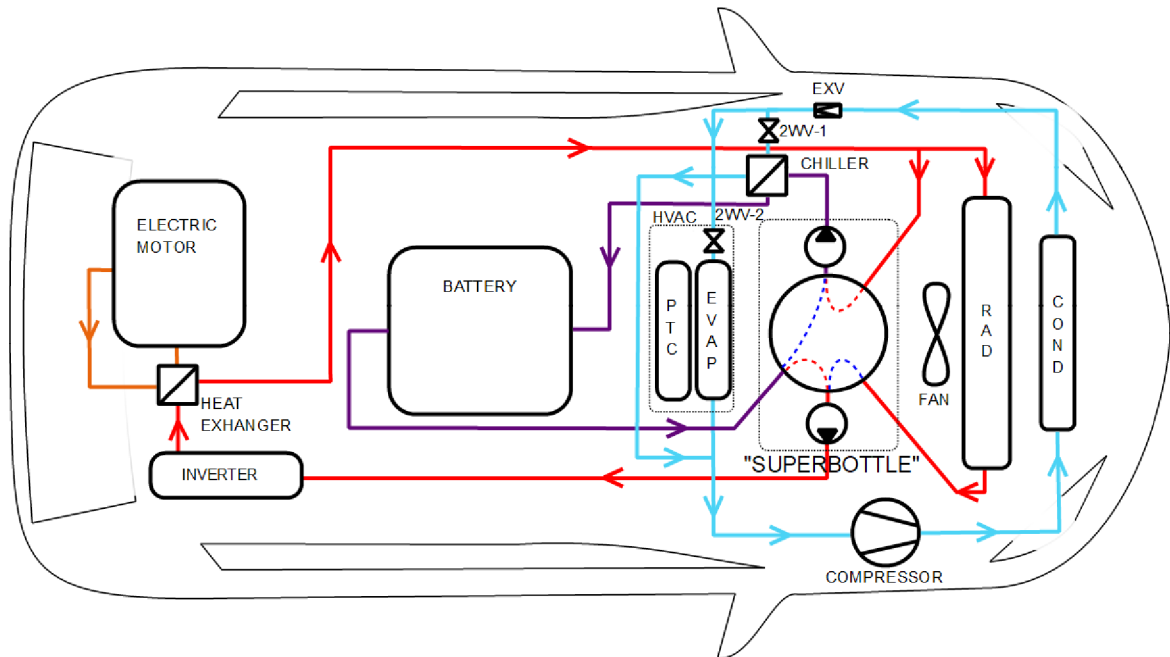


Figure 26. Tesla Model 3 thermal management design

So the cooling circuits work the same as in the case of the Hyundai Kona. There are only 3 small differences. The first one is that the motor is connected to the main circuit by a heat exchanger, because motor is cooled by oil. In addition, there is no mode for very low temperatures, so all heating of the battery is provided only by the motor with an inverter. Interesting part is the unification of the control elements into one module, this part Tesla calls the "superbottle" (Figure 27) in which combines 2 electronic pumps, a reservoir and a 4-way valve. The valve has two modes, in which, as same as the Hyundai Kona, it separates the battery loop for cooling and unites it for heating (the valve paths are indicated in the picture by blue for cooling and red for heating) [47].

The advantage of this solution is to save space and weight of components, facilitate serviceability and assembly during production. A disadvantage may be the fact, that in the case of a fault the entire module must be replaced instead of individual components, which will have negative effect on the price [47].

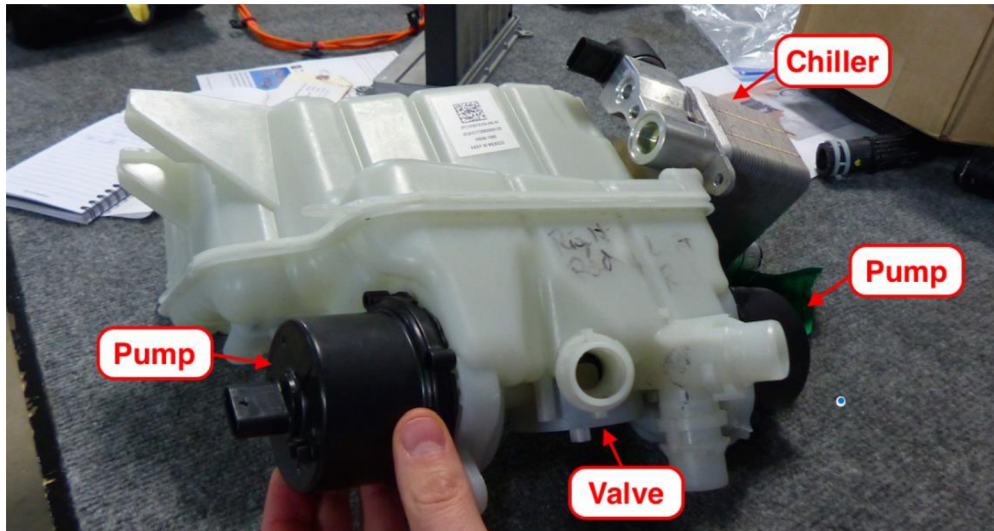


Figure 27. Tesla Model 3 “Superbottle” module [47]

4.1.3 CONCEPT 3

The most advanced thermal management systems can be considered to those, that can use waste heat to the maximum, which means not only for heating the battery, but also for heating the interior. For this, a heat pump system is used, which is standard in most electric vehicles, or as part of additional equipment.

4.1.3.1 HYUNDAI KONA (WITH HEAT PUMP)

Back to the Hyundai Kona, this car can be offered in a version with a heat pump. This system first appeared in the Kia Soul, but Hyundai has improved it further with a way to cool the battery. The basis is the same as for the version without a heat pump - 2 connectable loops with a battery and second with motor and inverter. Instead of air conditioning loop car contains heat pump loop (green line). There is also a second chiller (2), whose task is to use residual heat from the motor and inverter to heat the cabin. The second source of heat is from the outside environment [51], [52]. The heat pump here works in 3 modes:

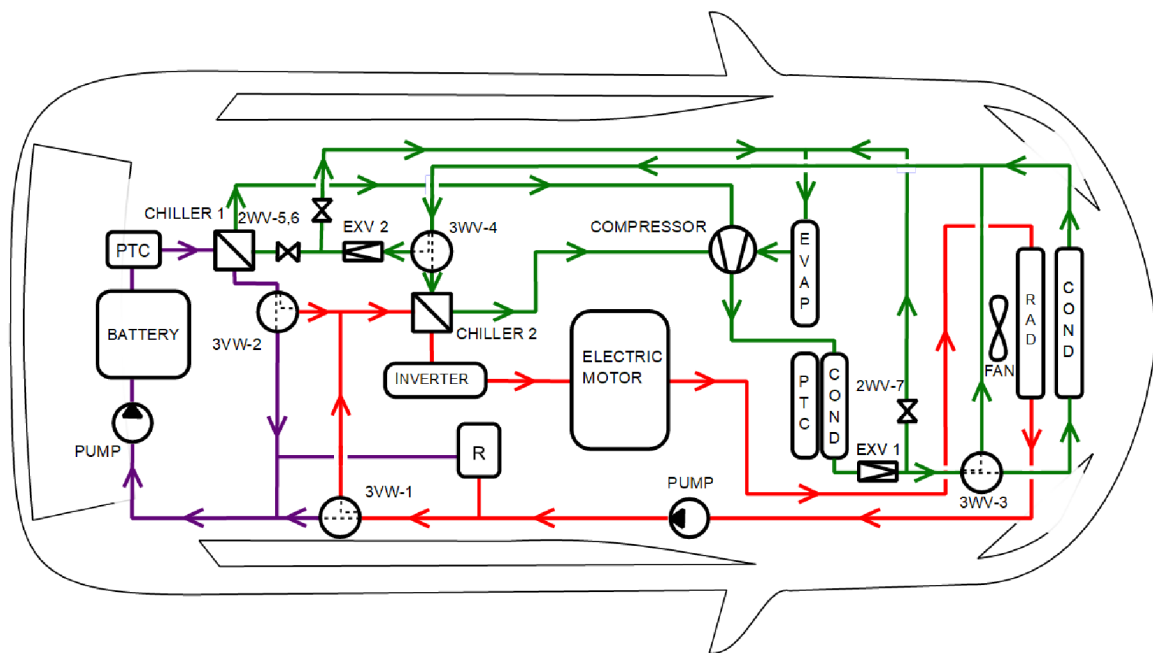


Figure 28. Hyundai Kona thermal management design (with heat pump)

Mode 1 – Cabin Heating

The heat pump works here as follows. The compressor compresses the gaseous refrigerant, which travels to the inner condenser, where the refrigerant heats the cabin. If additional heating is necessary, the air PTC heater can also be activated. Subsequently, the temperature in EXV 1 drops so that the refrigerant can absorb the outside heat in the front condenser. Through the 3WV-4, the flow is directed to the chiller (2), where it takes the heat from the battery, inverter and motor. Refrigerant returns to the compressor, the whole cycle repeats [51], [53].

Mode 2 – Cabin Heating with Dehumidification

In case if it is necessary to reduce the humidity in the vehicle for the purpose of defogging, the arrangement is similar to that in mode 1, only 2WV-7 is also opened here, which sends additional refrigerant to the inner evaporator [51], [53].

Mode 3 – Cabin Cooling

Again, path starts in compressor. Hot refrigerant still flows into inner conditioner, even when cooling is required, but HVAC flaps prevent the transfer of warm air. Refrigerant then travels to the EXV 1, but it is not active in this mode, so there is no drop in pressure or temperature. Next, cooling takes place in the external condenser, after which the refrigerant is directed to the EXV 2 using the 3WV-4, where the temperature and pressure drops. Using 2WV-5 and 2WV-6, the refrigerant is divided into the chiller (1) or evaporator as needed. Both paths are connected in the compressor, then the cycle is repeats again [51], [53].

4.1.3.2 TESLA MODEL Y

Even the Tesla car company was not left behind with the development. In 2019 came out with the Model Y, which was the first Tesla which uses a heat pump system, and not just any ordinary one. It is an extremely complex thermal management system using an 8-way valve for control, after which the whole system was named the Tesla Octovalve. Its complexity lies in 15 different modes - 12 heating and 3 cooling, the aim of which is to move waste heat between specific components and thus achieve maximum efficiency [54], [55].

The thermal management system can be divided into 2 basic circuits - heat pump circuit (green line) and water coolant circuit (red line). The heat pump circuit contains a compressor, cabin evaporator, cabin condenser, chiller and liquid cooled condenser (LCC). The last two mentioned components are plate heat exchangers between the two circuits, where evaporation or condensation can also take place. There is a 3WV behind the compressor, which can direct the refrigerant in 3 directions: to cabin condenser, to LCC or both ways. This system does not include an external condenser [54], [55]. Second Water coolant loop contains the following subloops:

- Battery loop
- Inverter and motor loop (motor is on separate circuit due oil cooling, conneted through heat exchanger)
- Radiator loop
- Loop with Chiller
- Loop with LCC

The previously mentioned Octovalve takes care of connecting these loops. It is a very complex module consisting of many parts, including the integration of electronic pumps. The photos (figure 29) show the refrigerant (left) and water (middle) distribution assemblies. The coolant is then directed into eight channels which are connected by a single valve (right), while it can be in 4 states, which it will be explained in the next section.



Figure 29. Tesla Octovalve (56)

Heating Modes

Table 2. Heating modes of Tesla Octovalve system

Heating	Outside temp	COP	Needs heating	Source of heat	Special	Octovalve state	3 Way Valve State
Mode 1	> -10°C	>>1	Cabin	Outside heat + Compressor		4	To condenser
Mode 2	< -10°C		Cabin	Battery + Drive unit + Compressor		3	To condenser
Mode 3	< -10°C		Cabin	Battery + Drive unit + Compressor + PTC heaters		3	To condenser
Mode 4	< -10°C	=1	Cabin	Compressor + PTC heaters		3	To condenser
Mode 5	< -10°C	=1	Cabin + Battery	Drive unit + Compressor		3	Open
Mode 6	< -10°C	=1	Battery	Drive unit + Compressor		3	To LCC
Mode 7		>>1	Battery	Cabin + Compressor	Store heat from cabin into battery	3	To LCC
Mode 8		>>1	Battery	Cabin + Drive unit + Compressor	Store heat from cabin into battery	3	To LCC
Mode 9	> -10°C	>>1	Cabin	Battery + Drive unit + Outside heat + Compressor		2	To condenser
Mode 10			Cabin	Battery + Drive unit + Compressor	Defogging	3	To condenser
Mode 11			Cabin	Battery + Drive unit + Compressor	Frost removal	1	To condenser
Mode 12			Cabin	Battery + Drive unit + Compressor	Dehumidification	3	Open

The system provides 12 heating modes. The system makes the choice based on the options from which sources it can draw heat, while trying to achieve the highest COP. Mods 1-4 are used to heat the cabin, while mode 1 having the highest COP because it draws heat from the surrounding environment. With deteriorating conditions, modes 2 and 3 are activated, when the heat from the components is used and the PTC heater can be added. In the coldest conditions, when it is no longer possible to use the heat from the battery and the motor is activated in mode 4. So, the heat pump does not take heat anywhere, that is reason of working at COP=1, this mod can also be supplemented with a PTC heater. For the purposes of dehumidification cabin condenser and evaporator working together in mode 2,3,4,5,10,12 [54], [55].

Modes 5 and 6 work when the ambient temperature is very low and the vehicle will be driven in a short time, for this reason a quick warm-up is necessary, but it is not very effective, COP=1. In mode 6, only the battery is heated, which is typically used during charging [54], [55].

The following mods 7 and 8 are very interesting. If the warmed-up vehicle stopped for a long time, the heat will begin to escape to the surroundings through the not very well-insulated cabin. If we wanted to drive the vehicle again after a while, the heat would have to be produced again. That's why Tesla came up with the idea of "keeping" this heat in the battery, as its battery pack is better thermally insulated. The heat pump therefore simply moves the heat from the cabin (and the motor in the case of mod 8) to the battery. This can also be used on a sunny winter day [54], [55].

Mode 9 is similar to mode 1 in terms of heat usage but uses all heat sources only to heat the cabin, so it has the highest efficiency.

The last 3 modes have specialized functions for defogging, frost removal and dehumidification [54], [55].

Cooling Modes

Table 3. Heating modes of Tesla Octovalve system

Cooling	Needs heating	Needs cooling	Octovalve state	3 Way Valve State
Mode 13	Cabin	Battery	1	Open
Mode 14	Cabin	Battery + Drive unit	1	Open
Mode 15		Battery + Drive unit + Cabin	2	To LCC

The vehicle offers 3 cooling modes. In mode 13, it is necessary to remove the heat from the battery, but at the same time heat the cabin, which is done again with the help of a heat pump. This condition is typical for charging. The excess heat is then removed to the surroundings via the radiator. Mod 14 is the same, in addition the heat is removed from the motor [54], [55].

The last mod 15 aims to remove all heat to the surroundings from the motor, battery, and from the cabin.

Octovalve States

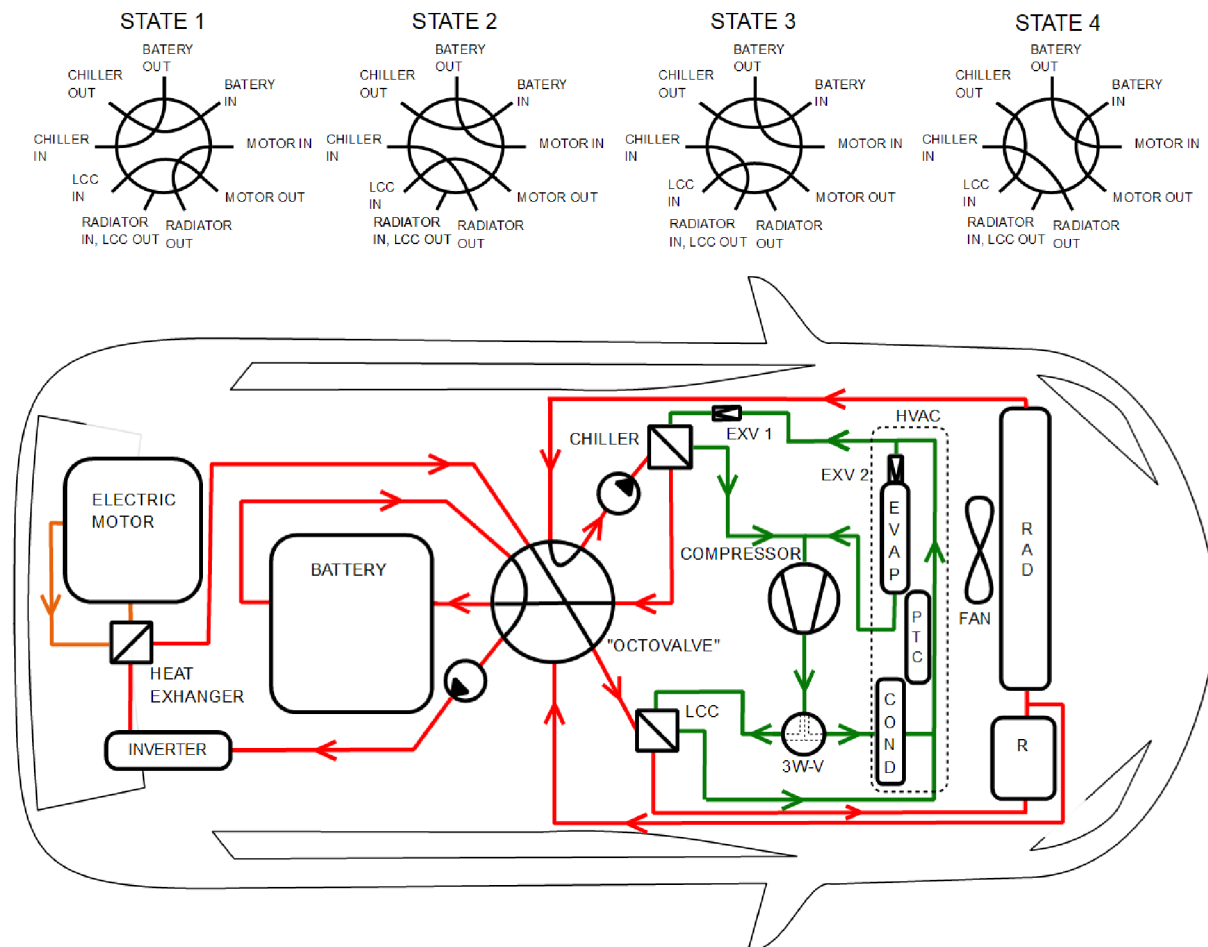


Figure 30. Tesla Model Y thermal management design with visualised Octovalve states

State 2

It will be explained the detailed function of the Octovalve system at example, when valve is in state 2 and mode 9 is activated, when the heat from all components is used to heat the cabin. The cycle starts with the compression of the refrigerant in the compressor. Using a 3WV, the refrigerant is directed to the cabin condenser, where it transfers heat. It then travels to the EXV 1 and is thus cooled. Then, in the chiller, it picks up the heat produced by the coolant loop, which is connected in series. The pump pushes the coolant into the chiller, followed by the battery, inverter, drive's unit heat exchanger, LCC (which is in this case inactive), followed by the intake of ambient heat by the radiator. The coolant returns and repeats the entire cycle [54], [55].

Mode 15 works similarly, when the valve is turned in the same state. Only the 3WV directs the flow to the LCC, where the refrigerant transfers heat to the coolant. Then refrigerant travels to the evaporator and chiller, where is cooled with the help of EXV 1 and 2 and is able to remove heat from the cabin and the circuit with the battery, motor and inverter. Finally, it travels to the radiator, where it gives off the excess heat to the surroundings [54], [55].

Other States

The functions of the system in other Octovalve states are similar, so others can be summarized as follows:

- In Octovalve state 1, the loop with the battery is connected only to the chiller, it is used in modes 13 and 14 for separate battery cooling.
- State 3 uses modes 2,3,4,5,6,7,8,10,11. The arrangement here is similar to state 2, but the coolant does not flow from the LCC to the radiator but returns back to the Octovalve.
- State 4 uses only mode 1. The battery with the motor and inventor has a separate circuit and is therefore not in contact with the heat pump loop [54], [55].

4.2 PLUG-IN HYBRID VEHICLES

This type of hybrid vehicle, which is capable of fully electric drive for a few tens of kilometers, contains all the basic components of a battery electric vehicle, but is additionally supplemented with an internal combustion engine. Ability to drive purely electrically brings the same problems, it is again necessary to heat/cool all components with regard to efficiency. The same applies to the heating of the cabin because the internal combustion engine is inactive during purely electric driving, so the energy for heating must be used from the battery [57].

4.2.1.1 CHEVROLET VOLT

This car can be considered as one of the first mass-produced plug-in hybrids. Sales of this car started already in 2010, and despite great expectations, the car was a sales failure due to the high price and little market interest [58]. However, even at that time, the car had a very complex, fully active thermal management, which is very similar to that of BEV's concept 2. This is common among PHEVs, for example the Volkswagen Golf [59]. It has the cooling of the electronics, electric motor with transaxle, internal combustion engine, heating and cooling of the battery solved. Each component here has its own cooling loop and there is no use of waste heat for heating the battery [60]. The loops are:

- Battery loop (red line)
- Power electronics cooling loop (green line)
- Engine cooling system and heat loop (purple line)
- Electric motor cooling loop (orange line)
- Air conditioning loop (blue line)

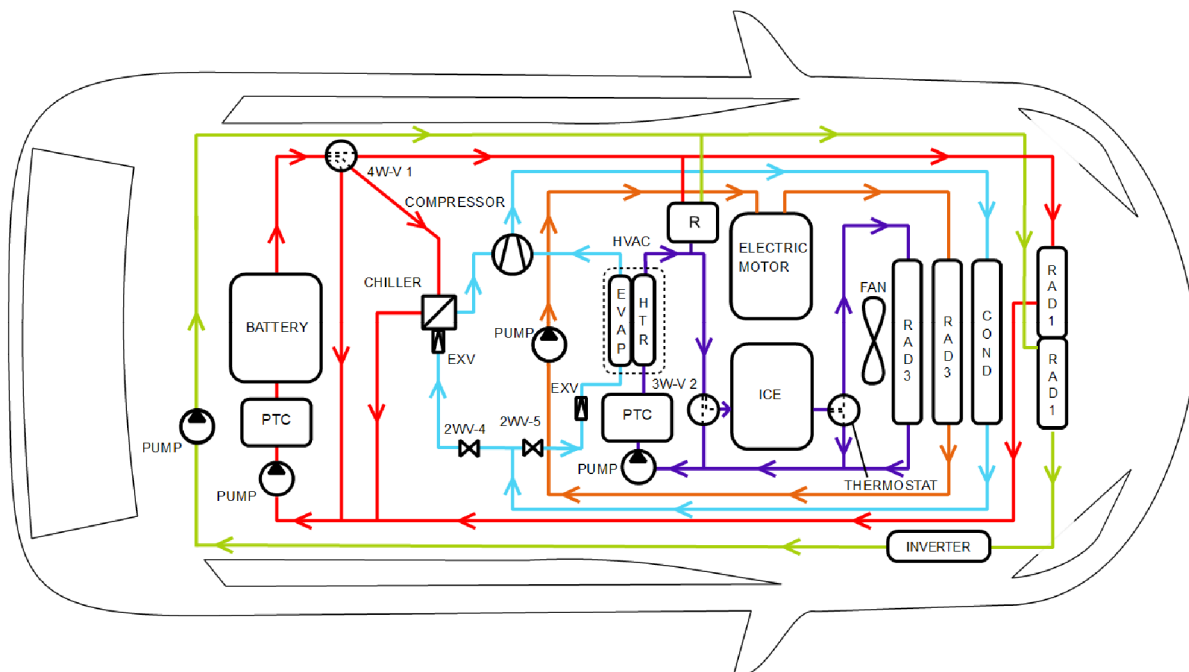


Figure 31. Chevrolet Volt thermal management design. ICE- Internal combustion engine

Cool Condition

In this case, battery heating works similarly to a BEV. 4WV-1 is switched to position where the circuit is shortened, and the PTC heater takes care of heating the coolant. When it comes to heating the cabin, it depends on whether the internal combustion engine is in operation. If not, the 3WV-2 will also shorten the circuit and another PTC will take care of heating the liquid coolant, which enters to the inner heater as soon as the internal combustion engine starts, the valve lets coolant into it and the heating starts to work like in conventional non-electrified cars [60].

Hot Condition

Cooling is provided by the already mentioned 5 loops, that contains 3 radiators (radiators for electronics and battery are merged in one assembly). Simple loops take care of the cooling of the electronics and the motor, their regulation is provided by increasing the input power of the pumps. In this case, the motor is cooled and lubricated with oil. Battery cooling also works in the same way as for BEVs, there are 2 modes, in first one the heat is removed by a front radiator, in the second case, when cooling is not enough, 4WV-1 switches to a circuit with a chiller, where heat is exchanged between the battery and air conditioning loops. Controlling temperature of ICE works in the same way as in a conventional car by opening the thermostat. If additional cooling is required, the fan is activated [60].

4.2.1.2 TOYOTA PRIUS

It should be mentioned that one of the most popular hybrids in the world is Toyota Prius, which was directly involved in the development of electrified transport, went on sale in 1997 in Japan. It was a full hybrid electric vehicle, but in 2019 this model also came with a plug-in hybrid version. However, the interesting thing is that even the latest models do not have an active liquid battery thermal management system, cooling is provided only by fan blowing cool air into the battery pack (figure 3). On the other hand, it already offers a heat pump system in the basic equipment, which is used for the cabin heating in purely electric mode [61]. The principle of its operation is the same as in the case of the Hyundai Kona, but it does not contain any heat exchangers for the use of waste heat.

4.3 FUEL CELL ELECTRIC VEHICLES

The fuel cell electric vehicle works on same principle as other electric vehicles, which means it has an electric motor, control electronics, a battery and, in addition, a fuel cell. Due to relatively high losses, the fuel cell is a large producer of heat. Unlike an internal combustion engine, almost no heat is removed through the exhaust, but into the cooling system, so it is necessary to use very powerful cooling. The advantage is that these losses can be used to heat the cabin. Only active cooling with water glycol-coolant is used for cooling the powerful fuel cells used in hydrogen cars [62].

4.3.1.1 TOYOTA MIRAI

Currently, there are only two hydrogen cars on the Czech market, namely the Toyota Mirai, which came on the market in 2021, and the Hyundai Nexo, which came a year later. Due to the age of both cars, availability of information of their thermal management are very limited. According to sources, we can at least roughly estimate the system in the Toyota Mirai [31], [63]. It consists of three loops:

- Fuel cell stack cooling loop (purple line)
- Power Electronics and electric motor cooling loop (red line)
- Cabin air conditioning loop (blue line)

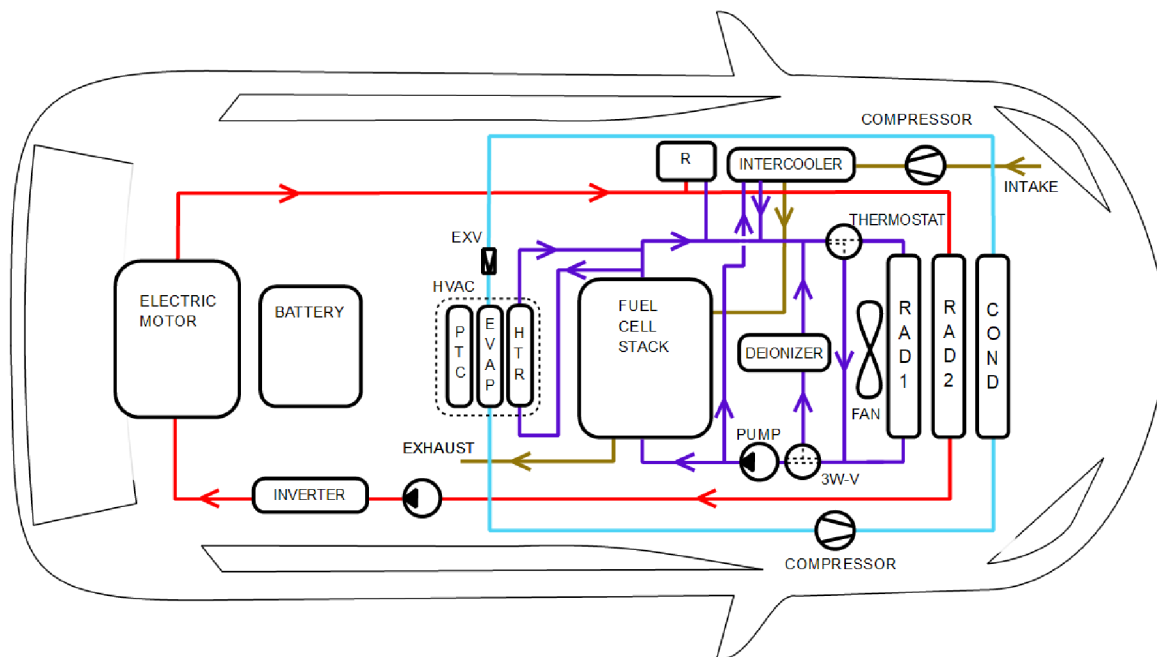


Figure 32. Toyota Mirai thermal management design

The first loop cools the fuel cell itself. The heat from it is received by the coolant, which is led by the thermostat into the radiator (1) or back to the circuit according to the required degree of cooling. If it's necessary, a 3W-V opens a loop with a deioniser, which removes electrical charge and to maintain a low conductivity of liquid [64]. A heater is used to heat the cabin. If the heat from the fuel cell stack is not enough to heat the cabin, e.g., at start-up, then a PTC heater can also be connected. This loop is also connected to the intercooler, which cools the compressed air flowing into the fuel cell stack, which figures in the chemical reactions that produce electrical energy [31], [63].

The second loop is used to cool the motor and electronics, heat is again removed out using a radiator (2) [31], [63].

The battery in which the energy is stored has a relatively small capacity of 1.24 kWh and does not have any active cooling [65].

EVALUATION

This thesis focuses on the thermal management of electric vehicles. In the first part, the thermal requirements on individual components are analysed. It has been found that each component has specific requirements in terms of operating temperatures, each additionally requiring different cooling or heating depending on external conditions such as charging, outside temperature, vehicle movement or the need of cabin heating. A specific part is the battery, if the operating temperature is not maintained in optimal range, its degradation is accelerated, which is especially disadvantageous considering the fact that the battery makes up about 40% of the price of a battery-powered vehicle.

The problem starts when a cabin or battery needs to be heated. Unlike vehicles with an internal combustion engine, all components of BEV and PHEV (in case of pure electric drive) vehicles have very high efficiency, so there is not enough waste heat to be used to heat the battery or cabin in very cold conditions.

The solutions are discussed in the last part, where the thesis investigate thermal management strategies used by current car manufacturers. Although not all of them have been analysed, because there is a limited amount of information on this topic. The strategies have undergone some historical development, while the first electric cars like the Nissan Leaf used passive battery cooling systems, where waste heat was not recycled in any way, the complexity of active thermal systems gradually increased in order to make better use of heat and cooling. Today, not only most EVs, but also PHEV vehicles such as the Toyota Prius offers heat pumps as standard, which allow transfer of thermal energy between individual components and also use heat from the surrounding environment. We can consider the solution used in the Tesla Model Y as a most complex thermal management, which is able to manage 15 different thermal modes depending on the conditions with the help of an 8-way valve named "Octovalve".

As far as hydrogen vehicles are concerned, the problematics has not yet been enough explored due to the very small number of vehicles on roads. However, thermal management here will not be as complex as with BEVs, because despite the increasing efficiency of fuel cells, there are large heat losses, so it is not necessary to deal with heat production as much.

With increasing demands on electric vehicles, we can also expect more frequent use of complex active heat systems and heat pumps in less or more expensive cars in the future, because the price of the system will not fundamentally affect the high price of the whole vehicle, in addition, the prices of the systems will probably continue to decrease thanks to new technologies and modularization of components.

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LIST OF ABBREVIATIONS AND SYMBOLS

<i>2WV</i>		2-Way Valve
<i>a₀</i>	[J·kg ⁻¹]	Specific work of the cycle
<i>BEV</i>		Alkaline Fuel Cells
<i>BTE</i>		Battery Electric Vehicle
<i>CNG</i>		Compressed Natural Gas
<i>COND</i>		Condenser
<i>COP</i>	[-]	Coefficient of Performance
<i>COP_c</i>	[-]	Coefficient of Performance for cooling
<i>COP_H</i>	[-]	Coefficient of Performance for heating
<i>DMFC</i>		Direct Methanol Fuel Cells
<i>ECU</i>		Electronic Control Unit
<i>EREV</i>		Extended-Range Electric Vehicle
<i>EV</i>		Electric Vehicle
<i>EVAP</i>		Evaporator
<i>EXV</i>		Expansion Valve
<i>FCEV</i>		Fuel Cell Electric Vehicle
<i>FHEV</i>		Full Hybrid Electric Vehicle
<i>h</i>	[J·kg ⁻¹]	Specific enthalpy
<i>HEV</i>		Hybrid Vehicle
<i>HTR</i>		Cabin Heater
<i>HVAC</i>		Heating Ventilation and Air Conditioning
<i>ICE</i>		Internal Combustion Engine
<i>IGBT</i>		Insulated-Gate Bipolar Transistor
<i>LCC</i>		Liquid Cooled Condenser
<i>Li-Ion</i>		Lithium Ion
<i>Li-Pol</i>		Lithium Polymer
<i>LPG</i>		Liquefied Petroleum Gas
<i>MCFC</i>		Molten Carbonate Fuel Cells
<i>MHEV</i>		Mild Hybrid Electric Vehicle
<i>MOSFET</i>		Metal-Oxide-Semiconductor Field-Effect
<i>p</i>	[Pa]	Pressure
<i>PAFC</i>		Phosphoric Acid Fuel Cells

<i>PEMFC</i>		Polymer Electrolyte Membrane Fuel Cells
<i>PHEV</i>		Plug-in Hybrid Electric Vehicle
<i>PMAC</i>		Permanent-Magnet Alternating-Current
<i>PTC</i>		Positive Temperature Coefficient
<i>q_C</i>	[J·kg ⁻¹]	specific heat supplied
<i>q_H</i>	[J·kg ⁻¹]	specific heat removed
<i>R</i>		Reservoir
<i>RAD</i>		Radiator
<i>REEV</i>		Range-Range extended electric vehicle
<i>S</i>	[J·K ⁻¹]	Entropy
<i>SOFC</i>		Solid Oxide Fuel Cells
<i>SOH</i>		State of Health
<i>T</i>	[K]	Temperature