

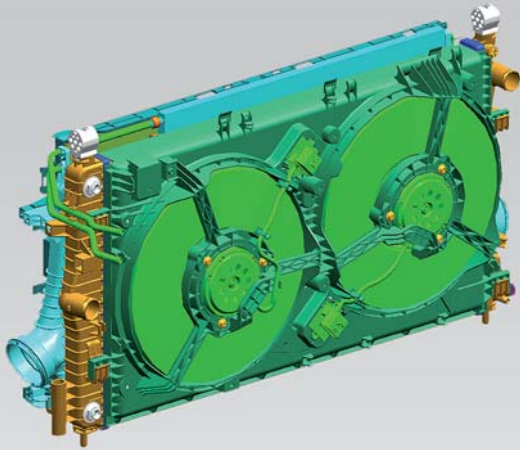
Technical Press Day 2009

Heat up. Cool down.

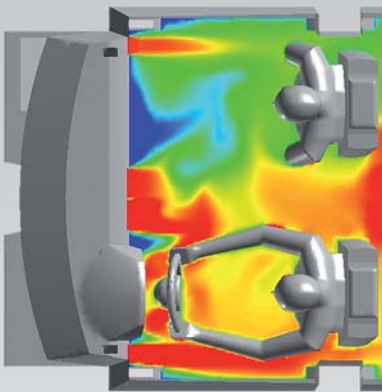
Thermal Management For Hybrid Vehicles

BEHR

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more than just another cooling task
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New vehicle designs require new A/C solutions



Editorial

Markus Flik
CEO



We became involved in this technology at an early stage and have already acquired extensive know-how in the field of thermal management for hybrid vehicles.

Ladies and gentleman,

Currently there is a clear trend towards smaller vehicles and downsized engines in response to the need for radically reduced vehicle fleet CO₂ emissions. One thing is certain: The growing demand for lower consumption and emissions in the coming years will lead to further enhancements in internal combustion engine design. In order to comply with future CO₂ limits, the larger-sized vehicles will, to a certain extent, be electrified.

So what line of approach must be taken as regards thermal management solutions for hybrid vehicles?

In hybrid vehicles, the electric powertrain emits very little waste heat. Consequently, the heat flows in the coolant will have to be better controlled by thermal management and the energy available in the exhaust gas used as an additional source of power. In future we will have to design our air conditioning systems much more efficiently so as to ensure a high level of cabin comfort in summer without compromising vehicle driving range.

To avoid premature aging of the temperature-sensitive lithium-ion cells, the Li-ion batteries will have to be interfaced with the vehicle A/C system. Electric vehicles with high driving ranges have two heat sources that both need to be cooled. That means that the engine cooling module has to include at least two radiators.

Due to the considerable complexity involved these future thermal management systems require close cooperation between the vehicle manufacturer and Behr as a systems supplier. That means that we also have to prepare ourselves internally for these new challenges. The cooling of the lithium-ion battery calls for multidisciplinary collaboration, combining as it does the know-how of traditional engine cooling with air conditioning expertise. We also need to understand the electrochemical processes that take place in the cell in order to be able to tailor our engine cooling concept accordingly.

As you can see, this is an exciting technology that also opens up new business opportunities for Behr. That's why we became involved in this technology at an early stage and have already acquired extensive know-how in the field of thermal management for hybrid vehicles. On the following pages you can see what technical solutions already exist for hybrid vehicles and where the challenges lie for future vehicle concepts.

Sincerely,

Markus Flik
CEO

Li-ion battery cooling: more than just another cooling task

Thomas Heckenberger,
Head of Technology Center



Li-ion batteries, however, can be used efficiently only within a specific temperature range up to 40°C. Especially in the summer months, a cooling of the battery must include the air conditioning of the vehicle.

The market for vehicles and off-highway vehicles is currently undergoing a period of historic upheaval. Under mounting pressure from emissions legislation and ever-increasing fuel costs, many manufacturers have taken to developing highly efficient drive systems or searching for viable alternatives to pure internal combustion engine technology for specific areas of application. This has led to a major trend toward drive train electrification, seen now in many different hybrid variants, or toward the production of purely electric-powered vehicles.

Li-ion batteries

The electric energy storage device remains the principal component of this technology. Lithium-ion batteries are considered the most attractive of all the currently available storage solutions, and are set to be used in next generation of hybrid and electric vehicles.

The advantages of this technology compared to conventional nickel-metal hydride batteries used to date include:

- Greater performance and energy density
- Highly compact physical dimensions
- High charge and discharge efficiency
- High cyclability

Lithium-ion batteries also have a long lifespan. Vehicle manufacturers must ensure that life spans of eight to ten years are feasible before initiation of series production, because it is unacceptable to inform the car buyer that battery replacement – associated with high costs – will be necessary after only a few years.

Li-ion batteries, however, can be used efficiently only within a specific temperature range: at operating temperatures of 40°C and above, the battery life span is reduced. At very low temperatures under – 10°C, battery performance declines and efficiency drops markedly. Finally, the permitted temperature gradient within a battery cell, and within a battery from cell to cell, is restricted to five to ten Kelvin.

Li-ion high-performance batteries are used in hybrid powertrains exhibiting exceptionally high dynamics. At times of momentary peak load, e.g. when braking (recovery (recuperation) of brake energy) and accelerating (assisted acceleration (boosting)), batteries must generate a high output within a very short time. These momentary peak load periods generate powerful electrical currents, causing significant warming of the Li-ion cells due to internal resistance. At around 95 percent, charging and discharging efficiency is very high; however, the resulting waste heat cannot be ignored. Coupled with the fact that, in the warmer weather and in warmer climates in particular, the temperature of the vehicle interior can rise to well in excess of 40°C, operating Li-ion batteries without cooling is not an option.

What happens if Li-ion battery cooling is insufficient or non-uniform? At high temperatures, the battery cells degrade more rapidly and their performance and capacity is reduced. As a result, cells fail to achieve the prescribed ten-year life span. A possible alternative is to deactivate the batteries when temperatures

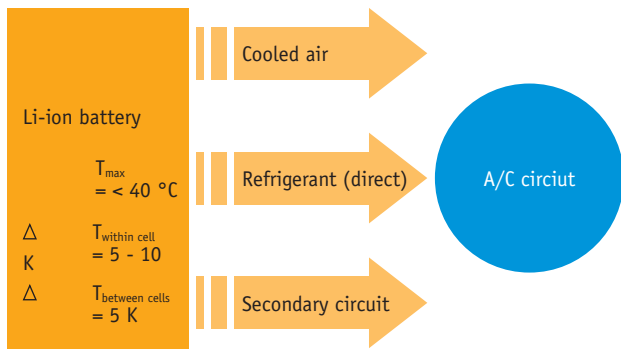


Figure 1 | Li-ion battery cooling

Good thermal conductivity:

- Along electrodes
- In the conductors
- In the metallic housing

Low thermal conductivity:

- Perpendicular to the electrode:
- In cavities

- ➡ Potential cooling contact points
- ➡ Heat flows

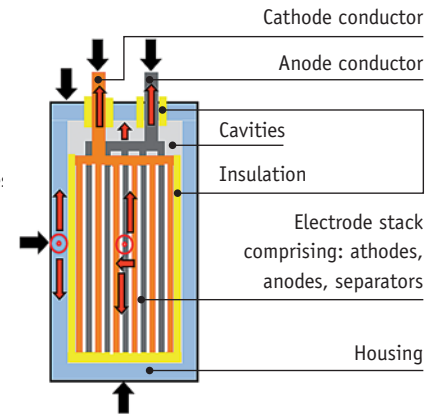


Figure 2 | Cell structure and cooling paths

exceed a set limit. All the advantages of the hybrid vehicle, however – electric boosting or recuperation of brake energy – would then be lost. For vehicles that run solely on electric power, this would even be impossible, since Li-ion batteries are the sole energy source.

Without adequate battery thermal management, calls for a ten-year life span are unrealistic. To meet these requirements, the cells must be kept in a thermally noncritical state below approx. 40°C in all operating conditions. To do this, efficient thermal management is required.

The requirements placed on the thermal management of Li-ion batteries are clearly beyond the capabilities of conventional engine cooling. There are three different approaches to cooling a Li-ion battery (Fig. 1):

1. Using cooled air. This is usually air conditioned air taken directly from the vehicle cabin or generated using an air conditioning unit installed specifically for the battery.
2. Using a supplementary evaporator in the form of a cooling plate installed within the battery. In this case, the battery cells are assembled on the cooling plate. This device contains channels in which refrigerant from the refrigerant circuit of the air conditioning system evaporates.

3. A heat exchanger (or “chiller”) transfers the low temperature produced by the evaporated refrigerant to a second circuit (secondary circuit) that, in turn, cools the cells in the battery. This too necessitates the installation of a cooling plate within the battery.

Cell structure, potential cooling paths, and cell types

Fig. 2 illustrates the schematic structure of a Li-ion cell. The cell is constructed from coated metal electrodes. These layers provide storage for the Li-ions. A non-conductive separator provides insulation between the positive and negative electrodes. This separator is conductive for the Li-ions, however. An organic solvent in which conducting salts have been dissolved serves as an electrolyte.

There are currently three different types of battery cell available (Fig. 3):

1. Round cells: anode, separator, and cathode are rolled up and inserted into a cylindrical housing made of aluminum.
2. Prismatic cells: flat-packed in a rectangular aluminum housing.
3. Pouch or coffee bag cells: the individual layers of active material are stacked or folded and packaged in a flexible aluminum composite film.

From a purely technical cooling perspective, the prismatic or pouch cells are most suitable for use in vehicles, because of the cell geometry. In round cells, relatively little surface area is available for transferring heat away from the cell interior. This leads to a greater internal/external radial

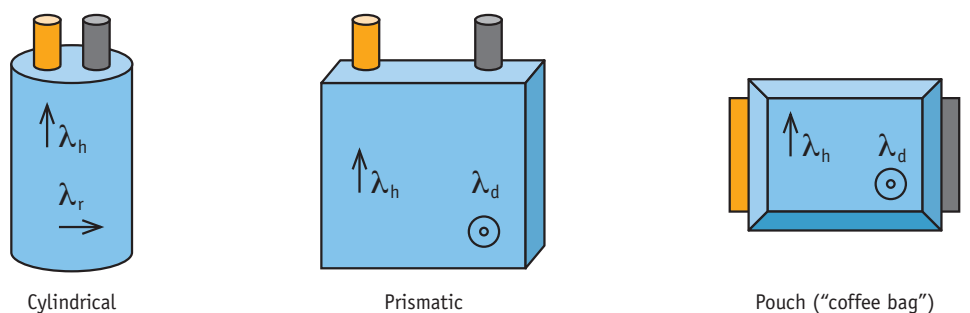


Figure 3 | Cell types

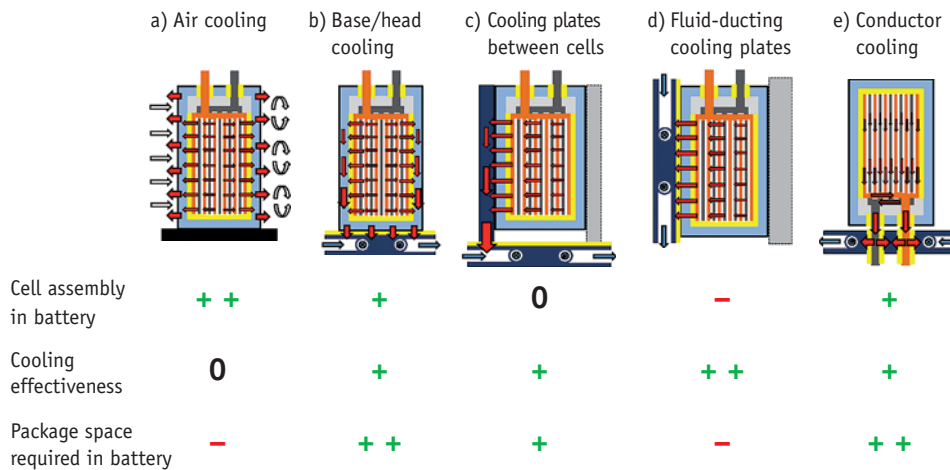


Figure 4 | Cooling concepts for cells

temperature gradient. Furthermore, the curved nature of the cells' external surface prevents optimal thermal contact with heat conducting elements that facilitate waste-heat dissipation to a heat sink.

Other important criteria influencing the choice of cell type, however, include production maturity, availability, safety, life span, and cost, which mean that the proven round cell continues to be used frequently.

In terms of a material's physical characteristics, sound electrical conductivity also means sound thermal conductivity. Thermal conductivity along the metallic electrodes is therefore two orders of magnitude higher than thermal conductivity perpendicular to electrodes. The reason for this is that the separators positioned between the electrodes act as thermal insulators.

Figure 4 illustrates the primary cooling concepts developed for cells at cell level. There are two contrasting designs: air cooling, and cooling via thermal contact. In the case of air cooling (Fig. 4a), cold air circulates around the cells, cooling the freely accessible surfaces. Any type of cell can be cooled using this method.

From a fluid mechanics perspective; however, the round cell offers certain advantages in this context. The cooling system interface is relatively basic. However, the space required to install cooling air channels between cells, supply and outflow ducts for the battery module, and a possible micro air conditioning unit is substantial. Furthermore, the cooling effectiveness is unsatisfactory, and cell cooling homogeneity is difficult to achieve.

A far more practical alternative in view of packaging space constraints and cooling efficiency are cooling methods in which the battery cells are positioned in thermal contact with a cooling unit with waste heat channeled to a heat sink. This, however, presents challenges of its own in terms of the design and configuration of the thermal contact unit, since, in many cases, electric insulation between the cooling unit and the cell housing is necessary. For low-height cells with sufficient wall thickness, thermal contact solely at the cell base or head is sufficient (Fig. 4b). In such cases, cells are simply positioned on a cooling plate. The cells can be very densely packed, and the required packaging space is therefore minimal. Pouch cells are unsuitable for this method of cooling,

since waste heat is primarily dissipated via the cell housing wall to the cell base from where it is transferred to the cooling plate. Pouch cells have a circumferential seam in the outer membrane that prevents optimal thermal contact.

If waste-heat dissipation via the cell housing is insufficient, heat-conducting elements in the form of heat conduction fins (Fig. 4c) or even fluid-channeling plates (Fig. 4d) must be installed between the battery cells. The latter, however, entails a significant assembly requirements in series production, since a large number of these plates need to be installed within the battery when cells are assembled.

Conductor cooling (Fig. 4e) constitutes a particularly efficient form of cooling, whereby the cell interior is cooled directly via the conductors and electrodes. To do this, the physical metallic route to the sequence of electrodes is used directly to establish a channel for good thermal conductivity. Pouch cells are particularly suitable for this method of cooling, since their conductors' flat design provides a contact surface of sufficient size. In all cases waste heat is channeled from the cells to the cooling plate, from where it is absorbed by either coolant or evaporated refrigerant and dissipated into the surroundings via the vehicle's cooling or air conditioning system.

Integration of battery cooling into vehicle cooling system

As mentioned at the beginning, integration of battery cooling in the air-conditioning system's refrigerant

circuit is essential because of the relatively low permissible operating temperature for Li-ion cells.

If the batteries are air-cooled (Fig. 5), cool air is drawn directly from the air-conditioned vehicle cabin or generated via a separate micro air conditioning unit (Fig. 6), a device similar to the rear HVAC unit in top-range vehicles. The installation space required for the air ducts leading to the battery and the weight of the blower or micro air conditioning unit are considerable, however. Potential noise disturbance in the vehicle interior resulting from the blower is an additional concern. Safety aspects relating to the use of vehicle cabin air warrant particular attention, due to the direct link between the vehicle interior and the battery interior.

Direct refrigerant-based Li-ion battery cooling (Fig. 7) is much more compact, whereby the battery evaporator is connected in parallel to the main refrigerant circuit and positioned directly within the battery itself in the form of a cooling plate. Only two additional refrigerant lines are required: a suction line and a pressure line. Waste heat generated by the battery is absorbed by the evaporating refrigerant. Coordinating the entire circuit is complicated, since two cold consumers with starkly contrasting operational properties must both be served by a single refrigerant circuit. A certain proportion of the air conditioning system's compressor output must be reserved for cooling operation, although this is small compared with the output required for the vehicle cabin air conditioning system.

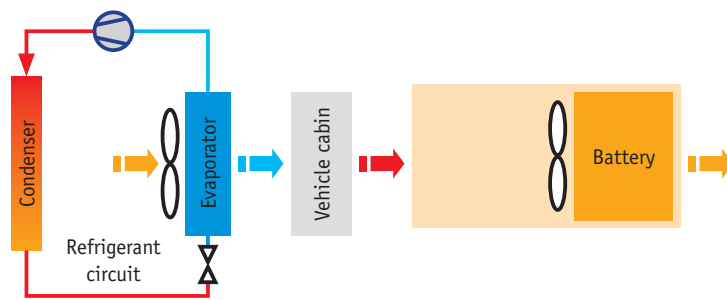


Figure 5 | Cooling systems for batteries – cabin air cooling

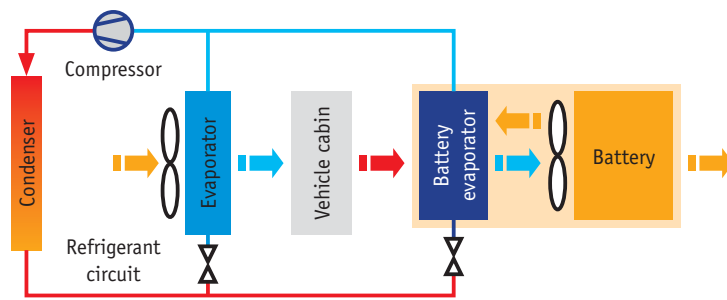


Figure 6 | Cooling systems for batteries – independent air cooling

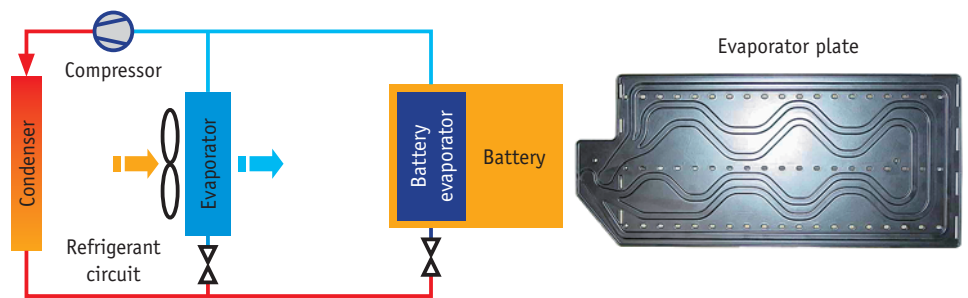


Figure 7 | Cooling systems for batteries – direct refrigerant-based cooling

This method of cooling means that the battery cannot be heated in winter. A cold battery is less powerful than a temperature-regulated battery, and at temperatures greatly below freezing will barely charge at all. This is tolerable in mild hybrid vehicles. In extreme cases, only limited hybrid functionality is available, although driving remains possible. In purely electric vehicles, however, prior battery heating must be ensured for the vehicle to be suitable for reliable winter use.

Refrigerant-based cooling is the preferred solution for mild hybrid

vehicles, since this entails the smallest installation outlay. The Mercedes-Benz S400 BlueHYBRID will soon enter series production, and will come equipped with a refrigerant-based Li-ion battery cooling system of this nature.

The issue of energy efficiency and cooling is vital with regard to larger batteries such as those used in plug-in and purely electric vehicles, since the energy required for cooling can directly impact the potential vehicle range. Moreover, the availability of electrical energy is also dependent on battery heating in extremely cold weather conditions (see above).

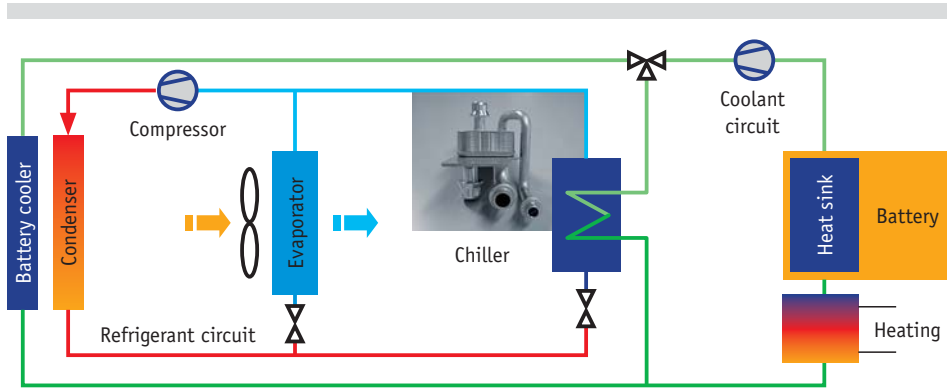


Figure 8 | Secondary circuit with chiller and heat sink in battery

Battery cooling via a secondary loop (Fig. 8) meets all of the above requirements. The battery is cooled via a separate coolant circuit. This secondary circuit operates at temperatures of approx. 15-30°C. An air cooler similar in configuration to a conventional engine radiator is sufficient to maintain these temperatures if external temperatures are low. If external temperatures exceed the predefined threshold, however, this secondary circuit must be additionally re-cooled by the air conditioning system's refrigerant circuit. To this end, Behr has developed highly compact, purpose-built heat exchangers called "chillers," designed to efficiently transfer waste heat from the secondary circuit to the evaporated refrigerant.

What does this have to do with energy efficiency? Cooling via a refrigerant

circuit consumes more energy than that used to operate a coolant circuit, since operation of the air conditioning compressor is necessary. This should therefore be avoided where possible.

In contrast to refrigerant, coolant can be heated, meaning that battery warming is possible. This facilitates efficient battery operation across an optimal temperature range. The potential energy source for battery heating is currently under discussion.

The price to be paid is higher space requirements, increased weight, and greater system complexity due to additional components such as pumps, valves, chillers, low-temperature radiators, etc. that naturally cost money. Initial series production orders for chillers and low-temperature

radiators of this nature have been received.

Current examples

Fig. 9 illustrates the Li-ion battery for the Mercedes-Benz S400 BlueHYBRID. The compact cooling device is not only responsible for cooling the battery cells, but also provides the fixture for the cells. The battery is cooled directly by the refrigerant which is incorporated into the vehicle's refrigerant circuit as an evaporator plate as illustrated in Fig. 7. The cooling device also consists of circumferential walling and numerous heat-conducting elements connected to the evaporator plate. These are responsible for cooling the internal battery area by assisting the conduction of waste heat from the cells to the evaporator plate. Channels are incorporated into the evaporator plate in which refrigerant is evaporated, taking up the waste heat from the surrounding cells. The channel structure has been selected specifically to ensure a homogenous temperature distribution across the entire plate. This degree of homogeneity coupled

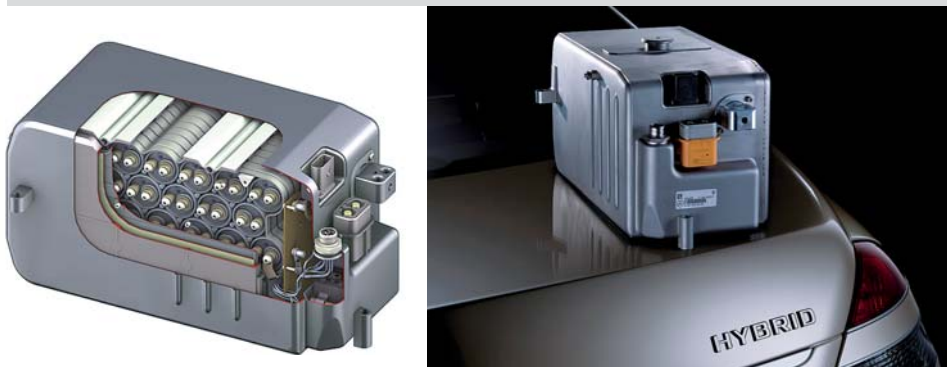


Figure 9 | Direct refrigerant-based cooling in Mercedes S400 BlueHYBRID



Figure 10 | Direct refrigerant or coolant-based cooling and conductor cooling

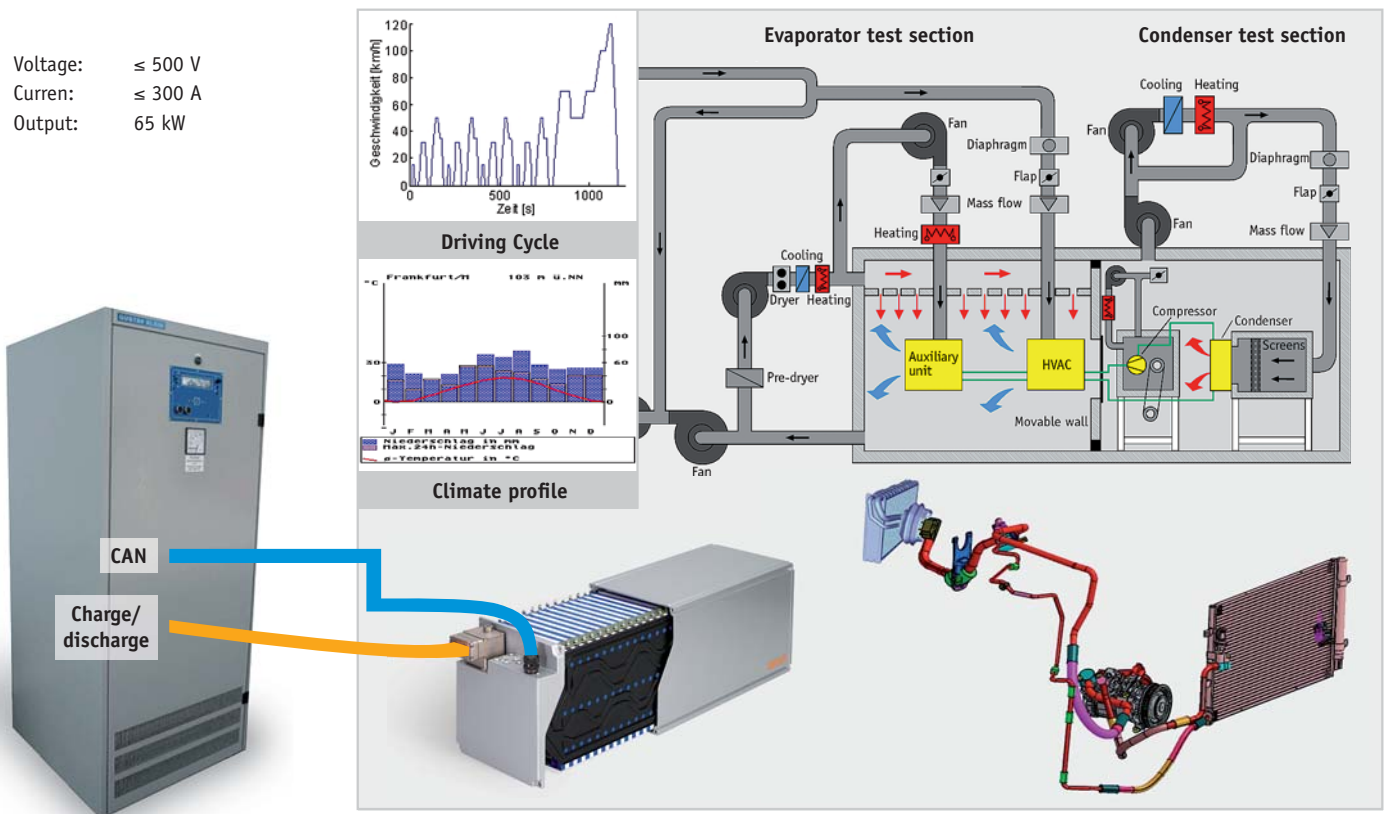


Figure 11 | HVAC/battery system test bench – battery, A/C circuit/secondary circuit under real operating conditions

with the simultaneous conductivity of waste heat in the cooling elements and container walling ensure that every part of the cell is cooled to the same degree.

As part of a joint research project funded by the German Federal Ministry of Education and Research, Behr worked closely with Li-Tec Battery GmbH & Co. KG and ISEA RWTH Aachen to develop an automotive-capable Li-ion battery prototype for use in hybrid powertrains (Fig. 10). To ensure the greatest possible packing density coupled with optimal thermal management and low overall weight, flat pouch cells are used, cooled via electric conductors. The package space of a standard H8 size lead battery is sufficient for 38 battery cells, each with a capacity of 6 Ah, including battery management system and thermal management.

Summary

There is no single “true” concept for cooling Li-ion batteries. Various cooling solutions are feasible depending on the cell type and the battery’s application.

The ever-increasing complexity of cooling requirements calls for efforts in development to progressively intensify. Much can today already be pre-developed and analyzed virtually via numerical simulation. For validation purposes, however, trial-based validation remains necessary.

Behr has therefore developed a special and unique HVAC/battery system test bench that facilitates the operation of real batteries under real operating conditions coupled with a real refrigerant circuit (Fig. 11). This involves the charging and discharging of the battery throughout an arbitrary, customer-specific test

cycle. Using two separate climatic chambers (one for the battery and one for the vehicle cabin), the basic thermal conditions for the cooling system can be realistically reproduced.

Li-ion battery cooling is therefore more than just an additional isolated cooling task. In fact, it requires complex thermal management and careful analysis and harmonization of all applicable cooling and air conditioning systems and their components in the vehicle.

Cooling for extended range electric vehicles

Simon Edwards,
Head of Advanced
Engineering
Truck Cooling



Electric Range extended vehicles show two heat sources. Because of that, the cooling module differs from the cooling module of a traditional vehicle.

Without a doubt, vehicles will be powered electrically in the future, perhaps even assisted by fuel cells. What will be the role of conventional engine cooling in such vehicles? A current major drawback for electric vehicles is the range. A key step toward full powertrain electrification is the “extended range vehicle.” The aim of this document is to clarify the contrasting aspects and challenges faced when cooling the extended range electric vehicle compared with conventional engine cooling and the extent of Behr’s activities to date with regard to the cooling of such vehicles.

What is an extended range electric vehicle?

In a conventional powertrain, an internal combustion engine powers the wheels via the transmission (Fig. 1).

In mild hybrids, e.g. the Mercedes-Benz S400 BlueHYBRID (for which Behr supplies the battery cooling system), the combustion engine is assisted by an electric motor connected in

parallel. This facilitates the “start/stop” functionality. Additionally, the internal combustion engine can be downsized, owing to the additional torque supplied by the electric motor. In full hybrids, e.g. the Toyota Prius, the wheels can be driven solely by electric power in low speed and light load situations. As the technology develops, the battery will become increasingly important and the internal combustion engine downsized further. As the demands placed on the energy supplied by the motor engine increase, so too will the requirements placed on the battery. The ability to charge batteries over night (“plug-in”) is becoming increasingly desirable.

The next step is to separate the internal combustion engine from the powertrain and drive the vehicle solely with electrical motors. If the energy density required to do this could be generated, the internal combustion engine could be dispensed with altogether.

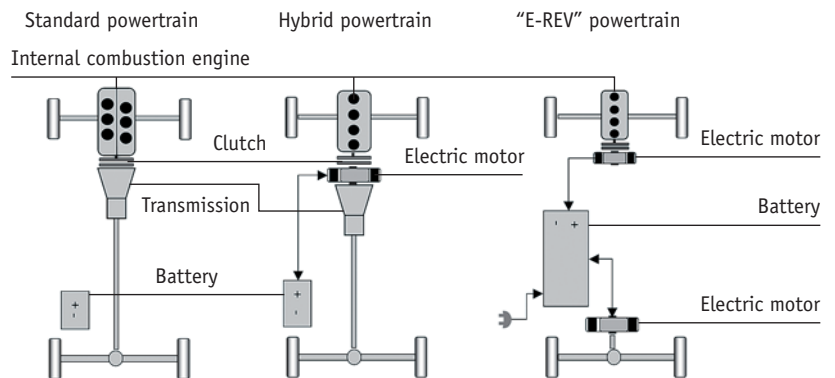


Figure 1 | Range extend electric vehicles

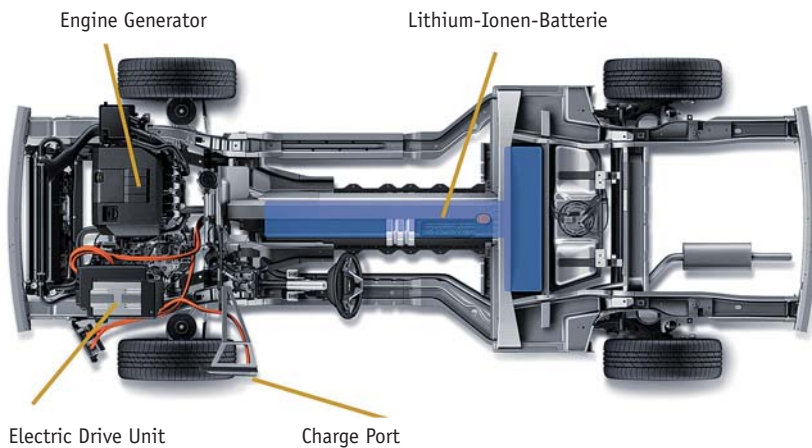


Figure 2 | GM Voltec platform

However, depending on the vehicle use profile, existing batteries for mid-range vehicles can achieve a range of up to about 50 km before recharging becomes necessary. This would be too short a distance for such a vehicle to become established in the market. The solution is to retain the internal combustion engine, downsizing it considerably, just for use as a series connected generator for charging the battery while the vehicle is in

motion. This approach helps to substantially increase the range of electric vehicles.

Probably the best-known example of such hybrid architecture is the Chevrolet Volt (Fig. 2), based on the GM Voltec platform. This can be configured for operation using electric power yielded from various sources. The vehicle is powered by an electric motor facilitating a potential range of up to 65 km.

The battery can be recharged overnight at an electric outlet directly via the plug-in port.

Cooling module for extended range electric vehicles

What sets this cooling module apart from the cooling modules of conventional vehicles with internal combustion engine powertrains?

The cooling module of the new Opel Insignia (Fig. 3), developed and supplied by Behr, is a typical example of a cooling module for a current mid-range vehicle without a hybrid powertrain. In Fig. 4 the various Insignia engines are detailed: gasoline engines ranging from 1.6 litres, I4 to 2.8 litres, V6 and a 2.0 litres, I4 Diesel engine. Power curves estimated by Behr for these engines indicate a range of 85 kW to 191 kW at 6,000 to 6,300 rpm for the gasoline engines and 81 kW to 140 kW at

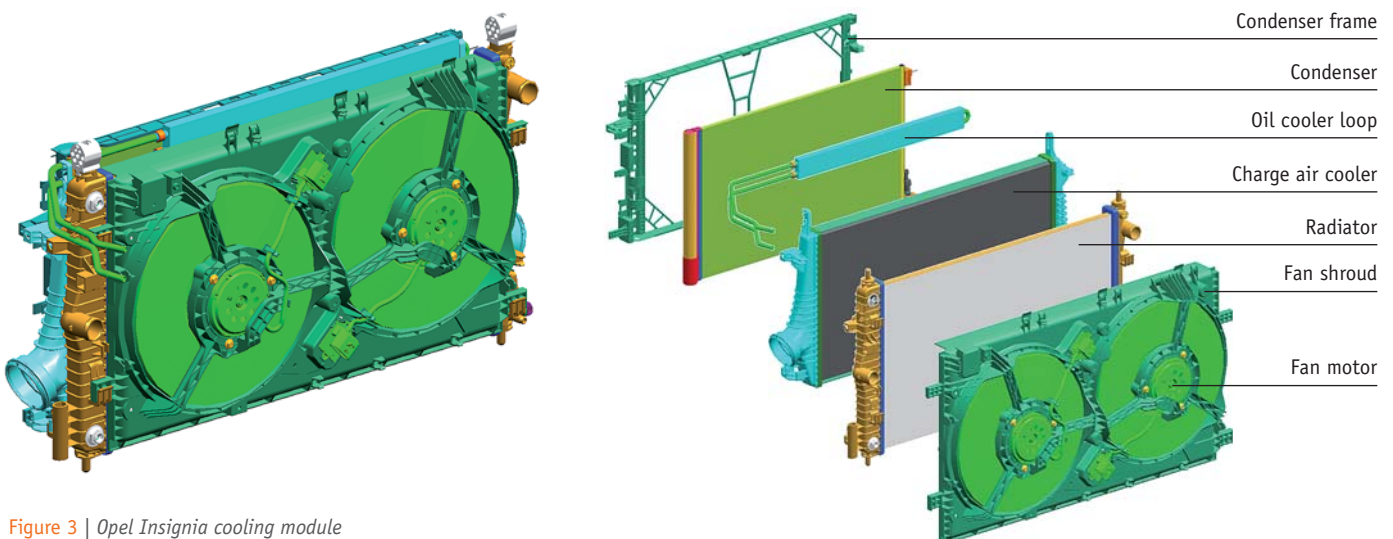


Figure 3 | Opel Insignia cooling module

Gasoline engines	1.6 ECOTEC®	1.8 ECOTEC®	1.6 Turbo ECOTEC®	2.0 Turbo ECOTEC®	1.6 Turbo ECOTEC®	2.8 V6 Turbo ECOTEC®
Drive	Front-wheel drive	Front-wheel drive	Front-wheel drive	Front-wheel drive	Adaptive 4 x 4 all-wheel-drive	Adaptive 4 x 4 all-wheel-drive
Low-emissions in accordance with	EURO5	EURO5	EURO5	EURO5	EURO5	EURO5
Fuel	Super	Super	Super	Super	Super	Super
Number of cylinders	4	4	4	4	4	6
Displacement in cm ³	1,598	1,796	1,598	1,998	1,998	2,792
Max. output in kW (HP)/at min ⁻¹	85(115)/6,000	103(140)/6,300	132(180)/5,500	162(220)/5,300	162(220)/5,300	191(260)/5,500
Max. torque in Nm/at min ⁻¹	155/4,000	175/3,800	230/2,000-4,000	350/2,000-4,000	350/2,000-4,000	350/1,900-4,500

Diesel engines	2.0 CDTI ECOTEC®	2.0 CDTI ECOTEC®	2.0 CDTI ECOTEC®	2.0 BiTurbo CDTI ECOTEC®
Drive	Front-wheel drive	Front-wheel drive	Front-wheel drive	Adaptive 4 x 4 all-wheel-drive
Low-emissions in accordance with	EURO5	EURO5	EURO5	EURO5
Fuel	Diesel	Diesel	Diesel	Diesel
Number of cylinders	4	4	4	4
Displacement in cm ³	1,956	1,956	1,956	1,956
Max. output in kW (HP)/at min ⁻¹	81(100)/4,000	96(130)/4,000	118(160)/4,000	81(100)/4,000
Max. torque in Nm/at min ⁻¹	260/1,750-2,500	300/1,750-2,500	350/1,750-2,500	260/1,750-2,500

Figure 4 | Different engines of the Opel Insignia

4,000 to 4,500 rpm for the Diesel engines (Fig. 5).

Since the majority of engines today are turbocharged and vehicle air conditioning also comes as standard, the Behr cooling module consists

of the components, illustrated in Fig. 3:

- A full face air conditioning condenser with a power of 18 kW
- A power steering oil cooler loop capable of dissipating 1.65 kW of heat

- A charge air cooler capable of dissipating 40 kW of heat
- A full face radiator with a performance of 150 kW
- An in-tank transmission oil cooler capable of dissipating 7 kW of heat
- A dual fan supplying up to 2.2 kg/s of air at 2,950 rpm.

How does this compare with the cooling module for a vehicle such as the Chevrolet Volt?

The first essential difference is that the sole purpose of the internal combustion engine is to supply electrical energy via a generator as required. A fuel cell is a viable alternative, although this example considers only an internal combustion engine.

Compared with the engines of the Opel Insignia, the engine for the Volt has been greatly downsized and simplified (Fig. 6). Although a turbocharged three-cylinder engine has been considered, the first engine likely to be used will be a non-turbo-

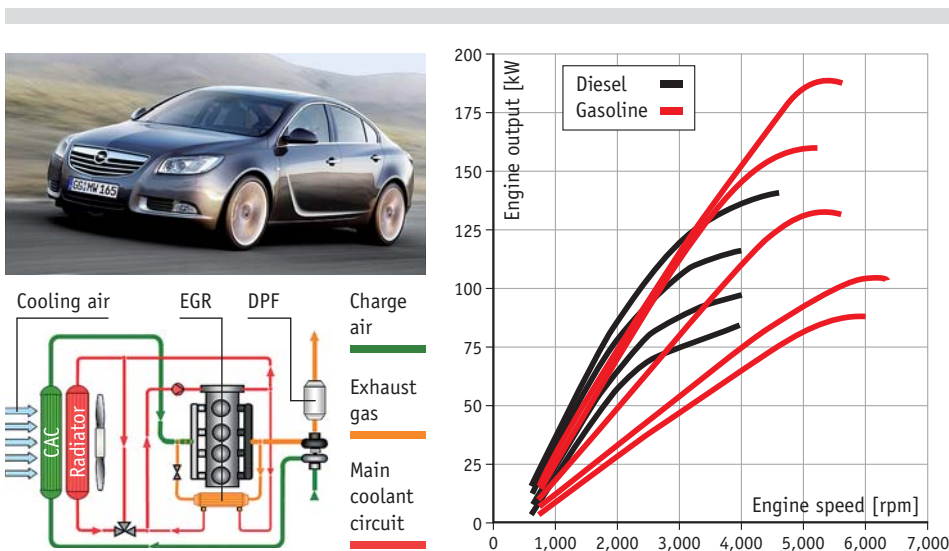


Figure 5 | Engine output and cooling circuit (Diesel engine) of the Opel Insignia

charged, 1.4 litre, in line four-cylinder gasoline engine with an output of 53 kW, capable of running on an ethanol mixture of up to 85 percent. Since the engine is not mechanically connected to the wheels, its rotational speed can be kept within a predetermined optimal range. This helps with the optimisation of the engine in terms of efficiency.

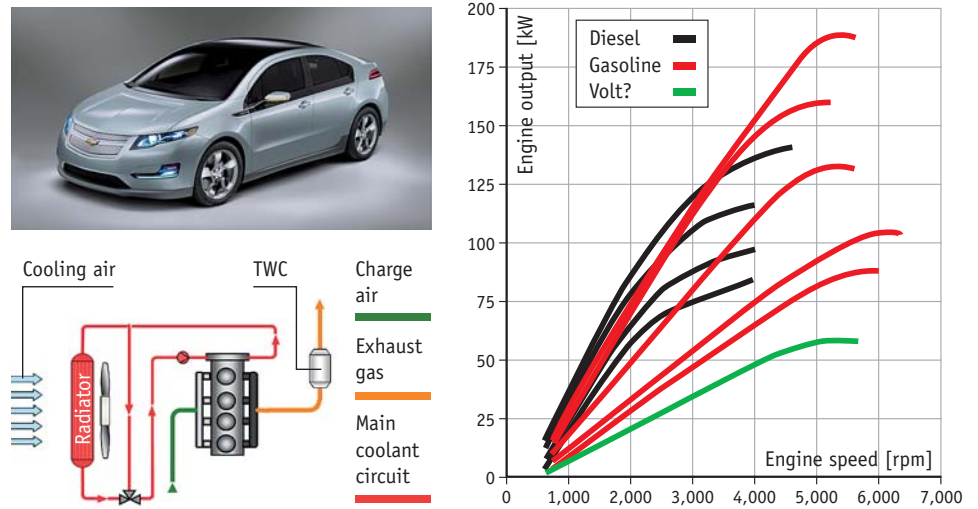


Figure 6 | Internal combustion engine of the GM Volt platform

What does the engine simplification mean for the cooling system?

As the engine used is a gasoline engine rather than a Diesel engine, exhaust gas cooling is not a prerequisite. Furthermore, the engine is not turbocharged, which means a charge air cooler is also not required. Since the engine has been greatly downsized and, in comparison with an Opel Insignia engine for example, is hugely simplified, the radiator should be simpler as well. Although this is the case, closer inspection reveals that cooling module is more complicated than expected.

- The fourth component in line is a high temperature radiator optimized for the downsized engine.
- Finally, a dual, brushless fan and the sealed cooling module frame ensure that the air flow through and around the cooling module can be controlled.

circuit of the Insignia or that of other conventional internal combustion engines. This is a level of complexity that only system suppliers such as Behr can truly develop

Examination of the necessary cooling circuit reveals that this is much more complex than the cooling

In reality, the cooling module for the Volt includes four heat exchangers instead of the characteristic three of the Insignia (Fig. 7):

- At the front of the module: a low-temperature battery cooler with a large surface area designed to keep the Volt's Lithium-ion battery at temperatures around 30°C.
- The second component in line is a full face condenser with output sufficient to maintain a comfortable temperature for the vehicle occupants.
- The third component in line (new component) is a radiator for the hybrid drive's power electronics unit.

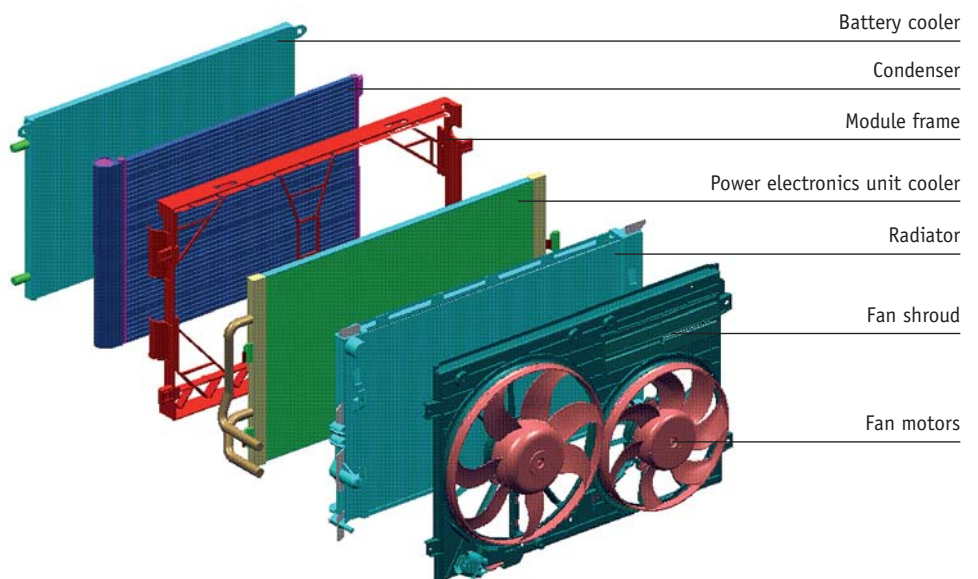


Figure 7 | Potential cooling module for an extended range electric vehicle

Thermal comfort in the vehicle – New vehicle designs require new A/C solutions

Peter Kroner,
Head of Advanced
Engineering,
Air Conditioning



In electric vehicles A/C comfort can directly affect potential range. Accordingly, as for all auxiliary equipment, energy must also be saved where possible in air conditioning.

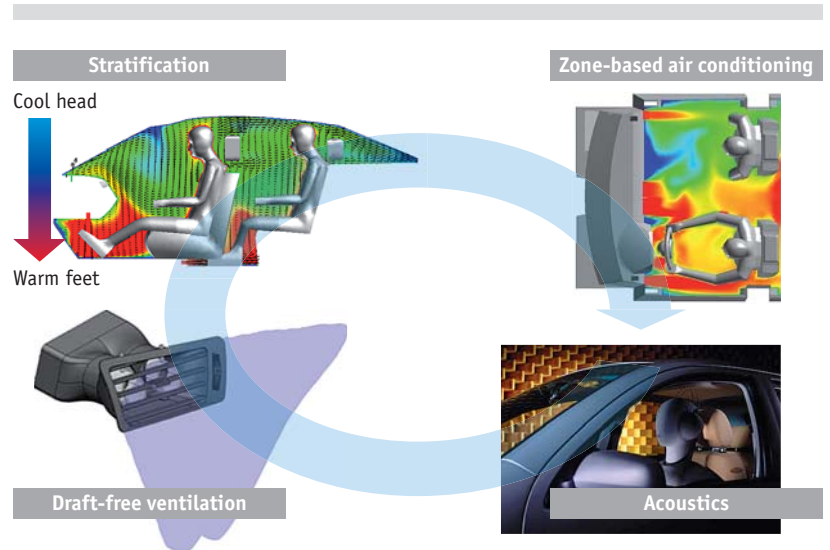


Figure 1 | Air conditioning comfort in the vehicle

The degree of climate comfort afforded by today's air conditioning systems is outstanding: variable air flows, vertical thermal stratification, pleasant acoustic properties, multiple climate zones, pleasant odors, different climate styles and more, Fig. 1.

New vehicle designs currently being developed, however, present entirely new challenges for air conditioning technology. In electric vehicles, for instance, A/C comfort can directly affect potential range. Accordingly, as for all auxiliary equipment, energy must also be saved where possible in air conditioning, e.g. through more efficient systems, new designs, and additional functionality such as cabin air conditioning before driving off. Lithium-ion technology in hybrid vehicles requires regulated battery cooling (or heating at low temperatures) to maintain battery life span and performance. Behr is developing solutions to all of these problems; those which are already available are presented in the following.

1. Vehicle design concepts

Fig. 2 illustrates the new vehicle designs concepts for corresponding classes of vehicle and their predicted market share in 2015. Internal combustion engine technology will persist in all vehicle classes for many years. Start/stop automation will likewise persist in all classes. Mild hybrids will remain exclusive to the top-range and mid-range classes, as will full hybrids. Electric vehicles will be primarily restricted to the small vehicles, and to some extent to compact vehicles.

1.1 Vehicles with internal combustion engines

Fig. 3 details the characteristics of the air conditioning system in conventional vehicles with internal combustion engines: refrigerant circuit driven by a refrigerant compressor powered by the engine via a V belt, and use of engine waste heat and potential exhaust gas heat for heating. Stringent requirements are

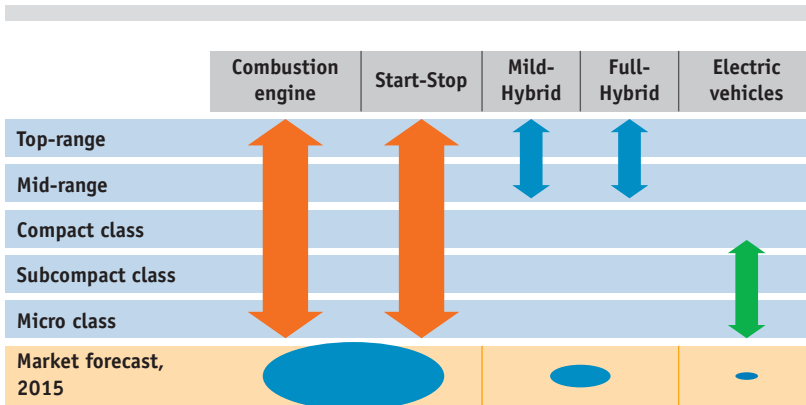


Figure 2 | Vehicle design concepts – Market forecast, 2015

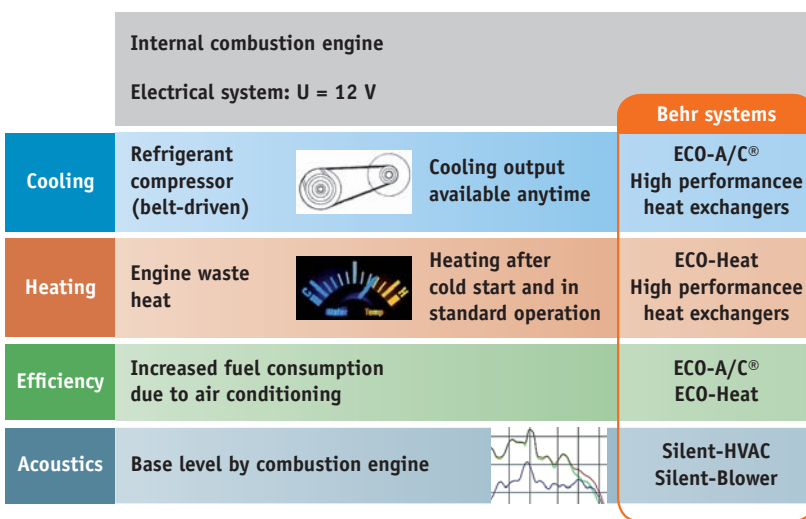


Figure 3 | A/C systems in vehicles with internal combustion engines

placed on air conditioning acoustics, which are affected and to some extent masked by internal combustion engine noise. Several key improvements have recently been made in this regard: HVAC modules with flow-optimized air ducts (silent HVAC), and low-noise blowers (silent blowers). (HVAC – Heating, Ventilating, Air-Conditioning).

In the case of conventional air conditioning systems (Fig. 4 illustrates a refrigerant circuit), the principal objective is to reduce the fuel consumption increase caused by the use of this technology. Behr has successfully developed the ECO-A/C® and ECO-Heat concepts specifically for this purpose, facilitating the following potential savings: for ECO-A/C®, a reduction of 20 percent between

2007 and 2012, and for ECO-Heat, a reduction of 30 percent between today and 2012, see Fig 5.

In the case of ECO-A/C®, this is achieved by:

1. High-efficiency heat exchangers within the refrigerant circuit
2. The use of an internal heat exchanger
3. An energy-saving adjustment to the refrigerant expansion valve on the evaporator unit

In the case of ECO-Heat, this is achieved by:

1. High-efficiency heat exchangers within the heating circuit
2. Air-side radiator cut off (radiator shutter)
3. Recovery of heat from the exhaust gas that can be used to heat

the vehicle cabin or to accelerate engine warmup

4. Partial recirculated air mode with controls eliminating the risk of windows misting up

Efficiency improvement measures associated with ECO-A/C® and ECO-Heat are also applied to air conditioning systems for new vehicle designs where possible.

1.2 Micro and mild hybrids

Micro hybrids are vehicles equipped with a conventional internal combustion engine and start/stop automation. Mild hybrids, however, are also equipped with a (small) electric engine and more powerful battery. The electric auxiliary drive is used exclusively to provide support when fast acceleration is needed, known as “boosting.” In mild hybrid vehicles, the battery is usually recharged by recovering brake energy. Fig. 6 details the characteristics of the air conditioning in each type of hybrid vehicle.

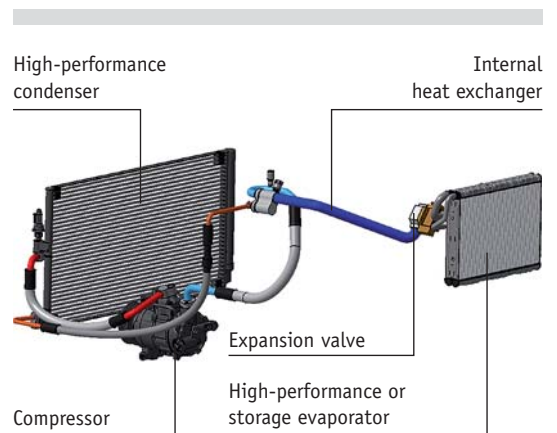


Figure 4 | Refrigerant circuit of an automotive air conditioning system

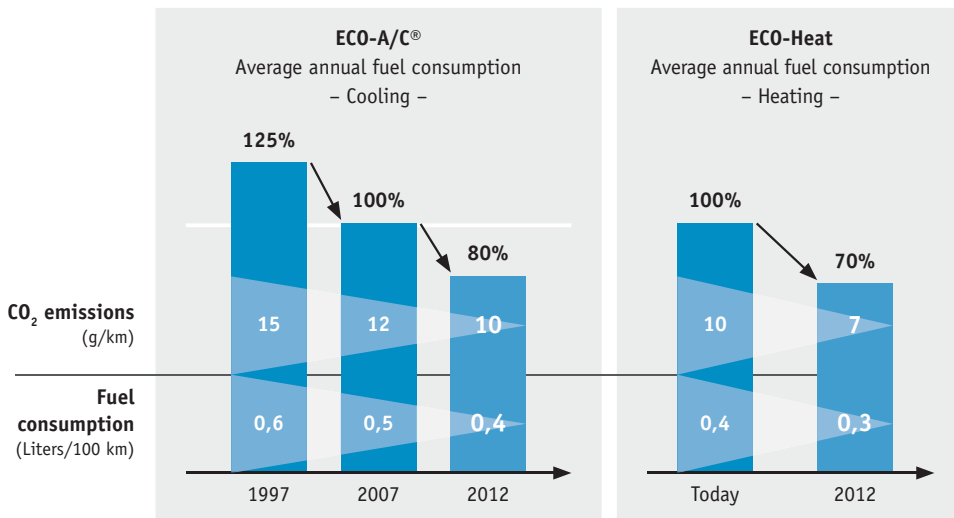


Figure 5 | Potential fuel consumption and CO₂ reductions using ECO-A/C® and ECO-Heat

Cooling: The air conditioning system is powered by a belt-driven compressor. Since compressor is inactive when the engine is idle, climate comfort in summer is maintained when the engine briefly stops (e.g. at traffic lights) by a cold storage device known as a storage evaporator.

Heating: Via engine waste heat, including use of residual heat during brief stops and/or via electric auxiliary heating (PTC heater).

A/C system acoustics: When the vehicle is idle, noise produced by the air conditioning system is no longer partially masked by engine noise, and thus becomes dominant. It was, therefore, necessary to improve the system acoustics to prevent the system noise from irritating vehicle occupants in the absence of engine activity, and, if possible, to produce a sound pleasing to the ear, even on a high blower setting. Improvements achieved via silent HVAC (Heating, Ventilating, Air-Conditioning) and silent blower technology play an important role.

Fuel savings via start/stop: Periods of engine stopping can cut fuel consumption by an average of up to eight percent in an urban traffic environment, provided a storage evaporator is used. Without this "cooling battery", the engine must be re-engaged, often long before the end of the period of inactivity, due to the rapidly rising internal temperature in warm weather conditions and/or the risk of odor build up, therefore cutting the start/stop fuel saving potential by roughly half.



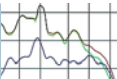
Electrical system:			
Micro => U = 12 V, start/stop			
Mild => U > 12 V, P _{el} < approx. 15 kW, start/stop, recuperation, Li-ion batteries			
			Behr systems
Cooling	Refrigerant compressor (belt-driven)	 No cooling during idle periods	ECO-A/C® Storage evaporator
Heating	Engine waste heat	 Residual heat and/or PTC during idle periods	ECO-Heat
Efficiency	Increased fuel consumption due to air conditioning		ECO-A/C® ECO-Heat
Acoustics	Idle periods without internal combustion engine noise		Silent-HVAC Silent-Blower

Figure 6 | Air-conditioning system in micro and mild hybrids



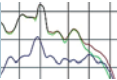
Electrical system:			
U >> 12 V P _{el} > approx. 15 kW, start/stop, recuperation, Electric-powered, plug-in charging, Li-ion batteries			
			Behr systems
Cooling	Refrigerant compressor (electric)	 "from battery" Engine-independent cooling possible	ECO-A/C® Battery cooling
Heating	Engine waste heat and/or electric	 Heating management necessary	ECO-Heat High-voltage PTC
Efficiency	Increased fuel consumption due to air conditioning		ECO-A/C® ECO-Heat
Acoustics	Idle and elec. powered periods without internal combustion engine noise		Silent-HVAC Silent-Blower

Figure 7 | Air-conditioning system in full hybrids

1.3 Full hybrids

Not only are full hybrids capable of “boosting,” but – depending on the electric system – they can often also cover substantial distances using electricity as the sole energy source. To achieve this, the vehicles are equipped with a complete electric powertrain, which of course requires a much more powerful battery than those used in mild hybrids. Nickel-metal hydride batteries remain the most frequently used type, although increasingly these are being replaced by high-performance lithium-ion batteries. Each of these battery types can be completely or partially recharged while the vehicle is in motion by converting brake energy (recuperation) into electric power. Fig. 7 details the characteristics of the air conditioning system in full hybrid vehicles.

Cooling: The electric compressor can be used to cool the vehicle cabin when the vehicle is powered by either the combustion engine or electricity, even if the engine (if powered by internal combustion) is temporarily idle due to congestion or other necessary vehicle stops, battery status permitting. Pre-cooling a hot vehicle cabin shortly before driving, via remote control for instance, is also possible. This significantly boosts the degree of comfort afforded by the air conditioning system since temperatures can frequently rise above 50°C or even 60°C when heat accumulates, causing discomfort to vehicle occupants without exception, even if these temperatures need to be endured only briefly upon activating the A/C system. Extended periods of engine-independent (or “no-idle”)

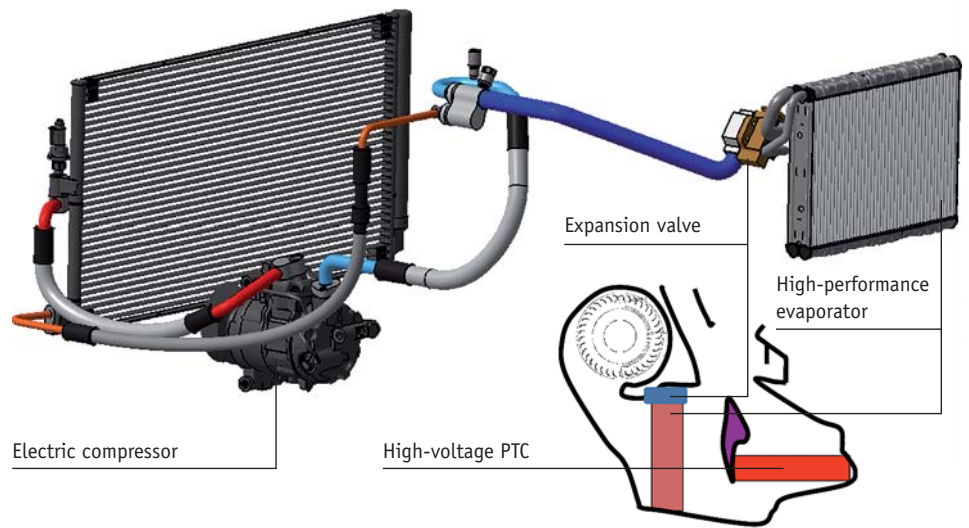


Figure 8 | Air conditioning system (refrigerant circuit and HVAC module) for electric vehicles

cooling are dependent upon available battery capacity.

Heating: Electric heating is necessary when the vehicle is powered solely by electricity, since only the internal combustion engine can deliver waste heat for heating purposes. This involves the use of a high-voltage PTC. Auxiliary electric heating is necessary if the internal combustion engine (when in use) fails to supply quantities of waste heat sufficient to meet this need. If this is the case, heating management is required.

Acoustics: Improvements to air conditioning system acoustics are more important for full hybrids than for mild hybrids because of the extended periods of internal combustion engine inactivity. Improved silent HVAC and silent blower components are also available for this purpose.

Battery temperature regulation: The growing trend toward high-performance lithium-ion batteries presents a new technical challenge: in order to safeguard durable and long-term operation, these batteries must be operated within a narrow temperature range. Where the battery

is cooled directly via the refrigerant circuit, onboard comfort and the battery itself, for instance, compete for energy. This poses the choice between regulating cabin temperature or the drive.

Plug-in hybrids: In plug-in hybrids, batteries can be recharged via an external electric outlet. This means that, if sufficient charge time has been allowed, the vehicle can drive off with a fully charged battery and a pre-heated or pre-cooled cabin. Rapid energy-intensive heating or cooling of the cabin is, therefore, no longer necessary.

1.4 Electric vehicles

The potential range of electric vehicles – an important criterion for their use – depends on both the performance capability of the battery and the efficiency of all the electricity consumers, including the air conditioning system. It was, therefore, necessary to greatly improve the efficiency of this system (illustrated in Fig. 8). To this end, Behr developed the ECO-A/C® system.

Fig. 9 details the characteristics of the air conditioning system in electric vehicles.




Electrical system: Battery and electric engine Extension: • Range extender Supporting measures in vehicle • Plug-in charging			
			Behr systems
Cooling	Refrigerant compressor (electric)		"from battery" Engine-independent cooling possible ECO-A/C® Battery cooling
Heating	Electric		Electric air or water heating High-voltage PTC
Efficiency	Air conditioning impacts on potential range		ECO-A/C®
Acoustics	Air-conditioning system acoustics unmasked		Silent-HVAC Silent-Blower

Figure 9 | Air-conditioning systems in electric vehicles with/without range extender

Battery cooling: See the corresponding information under "full hybrids."

1.5 Electric vehicles with range extender

One option to increase the potential range is to use a small onboard internal combustion engine to generate necessary electric power for the drive. This is also known as a "range extender."

Cooling: As with the full hybrid, cooling is provided by the electric compressor-powered A/C system. The vehicle can be pre-cooled before driving via an external power supply (plug-in charging). This can include parking spots equipped with a charge station.

Heating: Heating configurations can be either air or water-based. A high-voltage PTC is used for air-based heating. For water-based heating, the vehicle is equipped with a small, electrically heated water circuit. It is also possible to preheat the vehicle cabin via an external power supply.

Air conditioning system efficiency: With regard to air conditioning (cooling and heating), it is also necessary to consider improvements to vehicle cabin insulation or measures to reduce incoming solar radiation by shadowing window panes or reducing their transmittance in addition to measures to improve the efficiency of the A/C system itself.

Air conditioning comfort vs. potential range: It is also possible to reduce demands on air conditioning comfort in specific circumstances, e.g.

if it is possible to reach a destination or a charging station only by increasing the standard range. The ability to choose between a "comfort style," a "range style," and potentially a third "compromise style" is conceivable.

In the case of "range style," air conditioning could be reduced via, for example, slowing down the temperature pull-down rate in the cabin, a higher cabin temperature, or decreased airflow through the cabin. To enable drivers to determine the optimal style for their needs or those of other vehicle occupants, battery management must facilitate calculation of the effects of the selected style on the potential range and driving duration. A navigation device could be integrated to enable the necessary data (input of destination and route planning) to be queried effectively. This would also enable traffic reports to be taken into account.

Air-conditioning system acoustics: Special emphasis is placed on air conditioning system acoustics in electric vehicles, as it is in electric-powered full hybrids. This is because the masking noise of the combustion engine is absent.

The air conditioning system for electric vehicles with range extender works in the same way as that for electric vehicles without onboard electric power generation, although onboard power generation ensures that there is always sufficient power to operate the air-conditioning system, which means that it is not imperative to coordinate comfort, potential range, and driving style.

2. Air conditioning systems and components for new vehicle designs

2.1 Components for ECO-A/C® and ECO-Heat

Important components and measures for ECO-Heat und ECO-A/C® include (Fig. 10):

ECO-A/C®:

- High-efficiency heat exchangers
- Energy-saving adjustment of expansion valve
- Internal heat exchanger
- Control strategy, e.g. fresh-air/REC air control
- Energy-efficient electric assemblies

ECO-Heat:

- High-efficiency heat exchangers
- Radiator shutter

- Control strategy
- Exhaust gas heat recovery

2.2 Storage evaporator for start/stop automation

The storage evaporator consists of two cores: a main evaporator core and a storage evaporator core. During cooling operation, refrigerant is channeled through each core in parallel, during which the second medium in the storage core – a latent medium – is cooled to freezing point, thus acting as a cold storage unit. During periods of inactivity, the latent medium is no longer cooled and begins to melt. The thermal energy required to do this is drawn from the vehicle cabin air that flows through the cooling battery in recirculated air mode. The storage unit is subsequently charged by freezing the latent medium while the vehicle is in motion. At an evaporator inlet temperature of 25°C, the storage unit is recharged to 70 percent after 30 seconds and completely charged after one minute. Using a storage evaporator, cabin air conditioning comfort can be maintained in 95 percent of all idle periods in an urban traffic environment (as measured in Stuttgart).

2.3 High-voltage PTC

In the case of full hybrids and plug-in hybrids powered solely by electricity as well as electric vehicles, no engine waste heat is produced to heat the vehicle interior. Behr has, therefore, developed new high-voltage auxiliary heaters that ensure a comfortable onboard temperature in winter using its proven PTC technology. As with

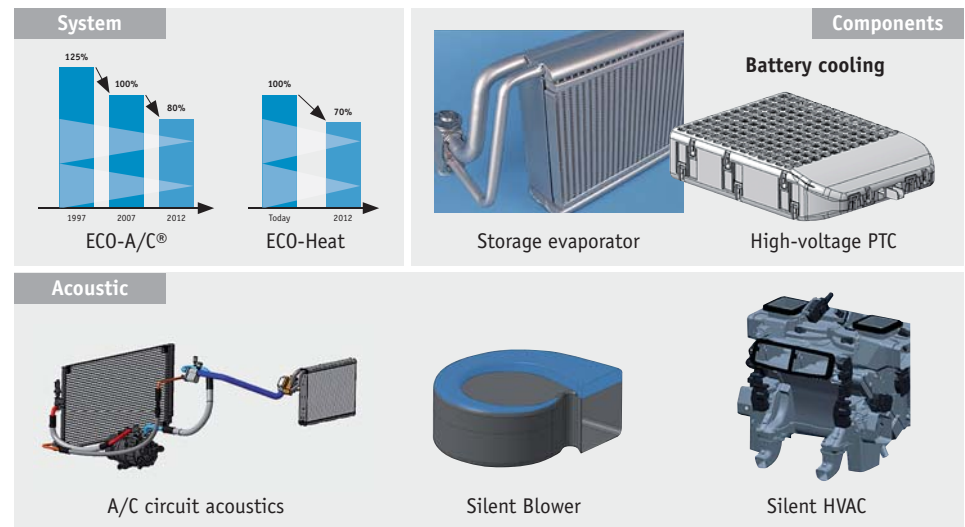


Figure 10 | Air conditioning systems and components for new vehicle designs

the PTCs currently used by Behr, these electric auxiliary heaters can be integrated into the HVAC module, thus saving crucial packaging space. Inherently safe high-voltage auxiliary heaters and the associated required output controllers are currently available.

2.4 Cooling systems for lithium-ion batteries

Behr has developed three separate cooling systems for the safe and effective cooling of Li-ion batteries:

1. Refrigerant-based cooling by way of connecting the battery to the air conditioning system's refrigerant circuit
2. Cooling via a coolant-based secondary cooling circuit
3. Cooling using air-conditioned air drawn from the vehicle cabin or (in winter) using outside air.

An additional evaporator must be fitted to the air conditioning system if it is used for cooling.

(Please refer to the following presentation held by Thomas Heckenberger for more detailed information regard-

ing these cooling systems: Cooling for range-extended electric vehicles)


2.5 Acoustics: silent HVAC

Refrigerant circuit: Certain modifications to the refrigerant circuit are necessary to increase efficiency. Specific measures are taken within the refrigerant circuit to alleviate the acoustic effects of these modifications. The aim is to apply specific improvements to facilitate reduction of the acoustic level to below the current standard to ensure system noise remains unobtrusive during idle periods or when the vehicle is electrically powered.

Blower (silent blower): Acoustically enhanced, low-noise blowers and improved blower motor decoupling arrangements have been developed to reduce blower noise.

HVAC module (silent HVAC):

The air ducts in the HVAC module are configured for optimal acoustics. New sound-transparent materials and resonance/interference sound absorbers are used to absorb unavoidable airflow noise.



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