Cooling Systems for Future Powertrains

Rainer Lutz, Matthias Jung, Laurent Art

MAHLE Behr GmbH & Co. KG, Stuttgart

Abstract. Beside optimized diesel powertrains new powertrain options, such as hybrid electric, battery electric or fuel cell electric, will be required to comply with CO_2 regulations and to reduce the carbon footprint of the transport sector.
Each of these powertrain options has special requirements to its cooling system in terms of heat rejection, target temperatures of the components involved and required coolant properties. Therefore, the solution for each powertrain looks different and has its own challenges. This significantly impacts the cooling system layout, the size of the heat exchangers and the fan power required to get the cooling task done.
This paper will describe the cooling requirements for optimized diesel, HEV, BEV and FCV powertrains and highlight the special challenges for each of them. Dedicated cooling system layouts will be presented, and the main thermal management components discussed.

Keywords: electric powertrain, cooling system, truck.

1 Introduction

In the last decades, heavy duty trucks relied on powertrains with internal combustion engines. With increasing awareness of climate change the greenhouse gas emissions of combustion engines including CO_2 need to be reduced. Legislators worldwide have enacted regulations enforcing a significant reduction of greenhouse gases. These targets are difficult to achieve with optimized combustion engines only. Therefore, alternative powertrains options get into focus. These options are:

- Hybrid powertrains (HEV)
- Battery electric powertrains (BEV)
- Fuel cell powertrains (FCV)

All these new options have their individual needs for thermal management. They differ significantly in their temperature targets, the amount of heat which needs to be rejected and the requirements for coolant qualities. All this has a significant impact on the cooling system layout, the hardware used and the controls.
The temperature targets depend on the components used in the individual system. Figure 1 illustrates the range of acceptable temperature for ICE's, fuel cells, electronics, batteries and cabins. The combination of heat rejection and temperature target defines the stringency of the cooling task.

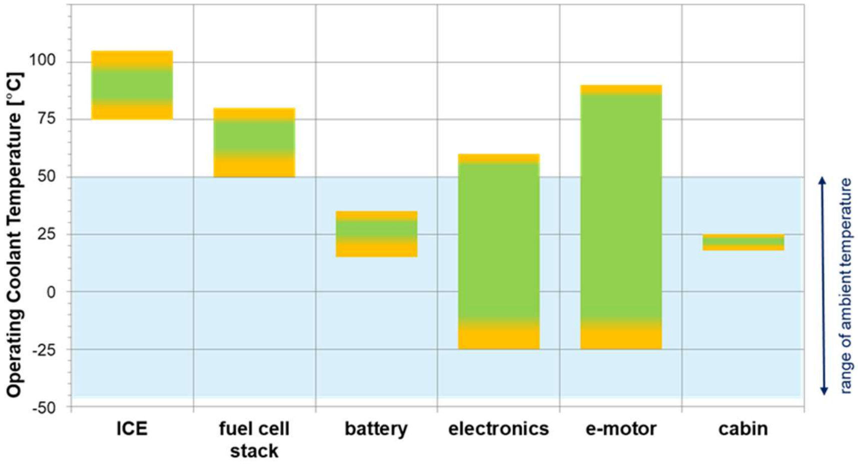

Fig. 1. Typical acceptable temperature range of powertrain components

In the last years many medium and heavy-duty trucks with electric powertrains had been presented to the public. When looking at their specifications you can see a significant spread in electric motor power as well of installed battery capacities (Figure 2).

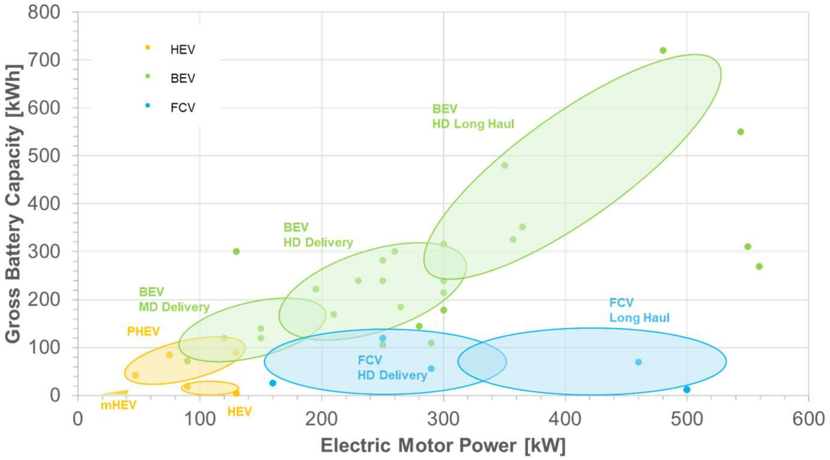

Fig. 2. Battery capacity and electric motor power of published electrified medium and heavy-duty trucks.

2 Powertrain Definition and Assessment for Cooling System Heat Loads

The different powertrain options are compared at a constant power to the road of 320 kW, which represents the high end of heavy-duty regional delivery and the low end of heavy-duty long-haul applications. Table 1 gives an overview of the powertrains assumed for this comparison.

	ICE	E-motor	Fuel cell	Battery
ICE	350 kW	--	--	--
mHEV	350 kW	24 kW	--	2 kWh
PHEV	350 kW	130 kW	--	100 kWh
BEV	--	350 kW	--	400 kWh
FCV	--	350 kW	300 kW	80 kWh

Table 1. Specifications of the different powertrain concepts as used for the cooling system assessment in this paper

Based on these assumptions, an energy balance tool was used to derive the heat rejections of each option. Using the energy balance of the total powertrain is important, as due to the efficiencies of each component involved the amount of energy changes from the energy source to the wheel. As an example, Figure 3 shows the energy flow from the battery to the wheel of the BEV concept at P_{Wheel}=320 kW. The decreasing energy flow from the battery to the wheel needs to be considered when calculating the heat rejection of each component. The diagram also illustrates why high efficiencies are important and have a high impact on the heat rejection. For example, if the efficiency of the traction inverter changes from 95 to 96%, the heat rejection of this component decreases by 20%.

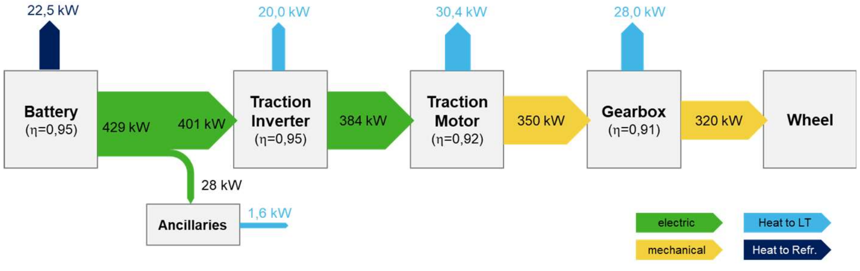

Fig. 3. Example of the energy flow of a BEV powertrain at p_{Wheel}=320 kW

Beside the heat rejection, each component has its temperature targets as shown in fig.1. When looking at powertrains at peak power and maximum ambient temperatures (in this case T_{amb}=35°C), all heat sources can be allocated to 3 different cooling circuits:

- High temperature circuit: $T_{coolant} > 60°C$
- Low Temperature circuit: $T_{amb} < T_{coolant} < 60°C$
- Refrigerant circuit: $T_{coolant} < T_{amb}$

Sometimes additional heat sinks are used, e.g., the battery may use an additional radiator to get cooled at low and moderate ambient temperatures directly without the detour via the refrigerant circuit.

Figure 4 shows the heat rejection for the investigated powertrain concepts, based on the energy flow analysis. The numbers shown reflect steady state conditions. In case of the refrigerant circuit the number represents the maintaining of cabin climate at T_{amb}=35°C in addition to the battery cooling needs. The component efficiencies used for the assessment reflect end of life conditions and are therefore a conservative approach.

The different powertrains show very different heat rejection patterns. With an increasing level of electrification, the amount of heat to the low temperature circuit and the refrigerant circuit gets higher.

For the hybrid powertrains, it's assumed that during ICE operation the electric motor is only used for boosting and recuperation. Therefore, when the vehicle is driving constantly uphill at peak power, there is no additional heat from the electric part of the powertrain and the heat rejection is the same as for the ICE. Pure electric operation is only foreseen for the PHEV concept when the ICE is off, e.g., driving in environmental zones. The heat rejection of this operation mode is also shown in Figure 4.

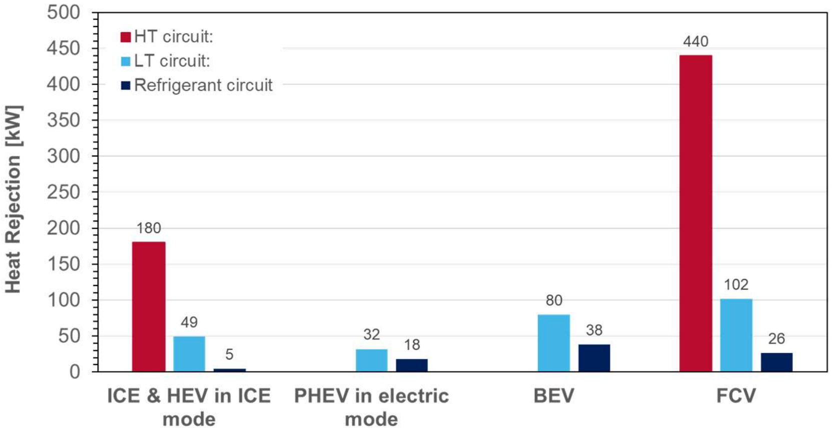

Fig. 4. Heat rejection to the cooling circuits of the investigated powertrain concepts at peak power and T_{amb}=35°C

The fuel cell powertrain differs from the other powertrains by its very high heat rejection to the high temperature circuit. Figure 5 compares the energy balance of a fuel cell powertrain with a conventional diesel engine. This rejects almost 50% of its losses via exhaust gas or radiation and convection. As the fuel cell works on a significantly lower temperature level, the heat flux via exhaust is very small. So almost the complete heat losses must be rejected via the high temperature coolant loop. Due to some additional fuel cell ancillaries like the fuel cell DC/DC-converter or the fuel cell cathode air compressor, the heat rejection to the low temperature circuit is higher as of the BEV concept, too.

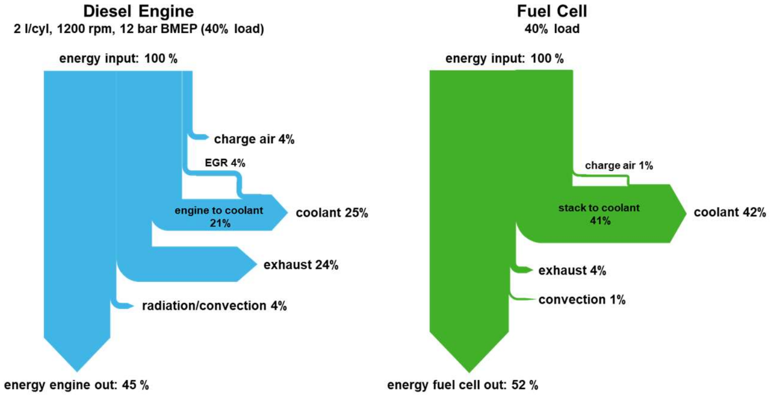

Fig. 5. Comparison of the energy balance of a diesel ICE and a fuel cell powertrain at road load conditions.

The required cooling air flow rates for each powertrain option can be estimated by combining the total heat rejection rates and the maximum temperature targets of each investigated powertrain option. The exact numbers depend on various parameters, such as exact size and design of the radiators, packaging space, component efficiencies, etc. The result of can be seen in Figure 6.

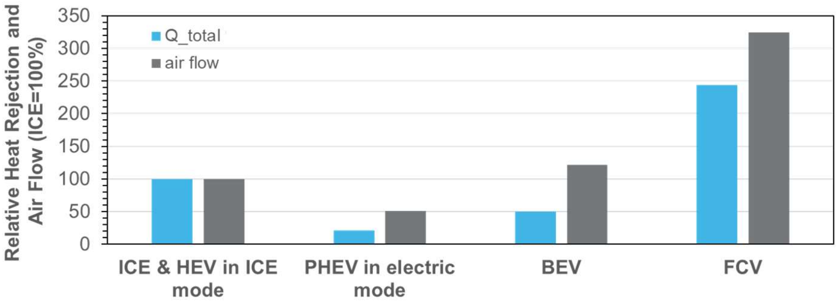

Fig. 6. Relative heat rejection and cooling air flow requirement at peak power and T_{amb}=35°C

3 Cooling System Layouts

The cooling circuits shared in this chapter are generic circuits, which are supposed to illustrate the special needs of each powertrain option. The actual cooling system for a dedicated vehicle may differ in many aspects due to components used, performance level, packaging situation, etc. So, the cooling system layout is always an individual answer on the actual needs of each application.

3.1 Internal Combustion Engines

Internal combustion engines are still the dominant power source for heavy duty trucks and will stay in this position at least until end of this decade.

The predominant cooling system architecture for HD trucks has not significantly changed since the introduction of charge air cooling in the 1980’s. Figure 7 shows a generic cooling system layout as used today for ICE powertrains. The cooling module is installed in the front end of the truck and includes a HVAC condenser, charge air cooler, radiator and fan. The fan is driven directly by the combustion engine via a fully modulated Visco clutch for fan speed control.

With increasing stringency of emission legislations worldwide, EGR coolers started to become part of the trucks cooling systems in 2000 [2].

With the introduction of Euro V, some engine platforms started to use indirect charge air cooling. In this system the charge air cooler in the front end is replaced by a low temperature radiator and the charge air gets cooled by low temperature coolant. Despite good performance and fuel consumption benefits of such systems [3], complexity and cost prevented indirect cooling system from becoming mainstream. Today they are only used on some high performance, two-stage turbo charged applications.

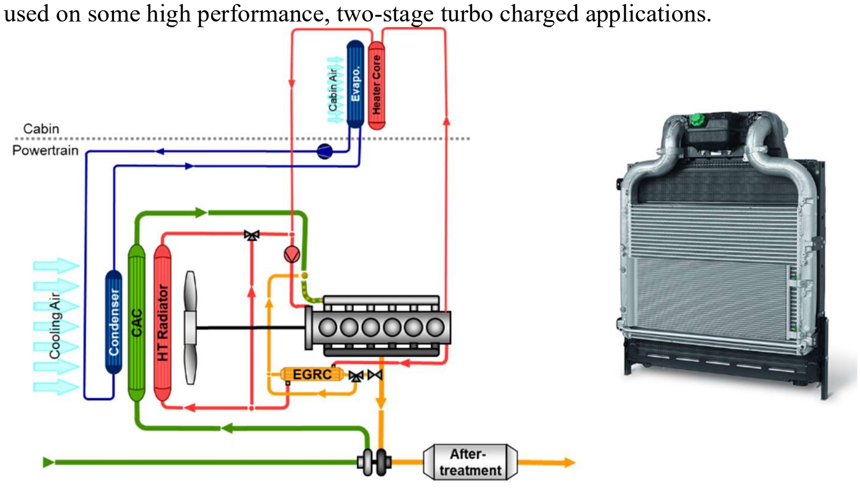

Fig. 7. Generic cooling system layout for internal combustion powertrains, MAHLE Euro VI cooling module

To cope with upcoming emission and fuel consumption regulation the ICE will be further optimized. Nevertheless, the basic cooling system architecture is not expected to change. The focus will be on optimized components like highly efficient charge air coolers and fans. To reduce cold start emissions, an EGR cooler bypass may be introduced.

3.2 Hybrid Powertrains

A hybrid powertrain combines the traditional diesel engine with an electric motor and a battery system. The battery delivers energy for operation of the electric motor and stores energy generated by the motor during braking. In addition, ancillaries like pumps, fans, HVAC compressors, ... may be electrified, depending on the level of hybridization. The variety of hybrid powertrain is quite huge. It ranges from so called mild hybrid systems to solutions that allow the vehicle to operate purely electric over a limited range.

48 V mild hybrid powertrain (mHEV).

The investigated mild hybrid entry system consists out of the 48 V motor, the battery and a DC/DC converter, connecting the 48 V with the 24 V voltage level of the vehicle. To keep the complexity of the system low, all components share a common low temperature cooling circuit (Figure 8). The total heat rejection of this circuit is 5,5 kW and the target for the cooling temperature at the battery inlet is 5K above ambient. This requires a radiator size of 25 dm² which can be placed either on the side of the vehicle or in the front end. Depending on the ram air support at the actual location, the radiator may need a fan up to 300 W. The coolant pump power is less than 50 W.

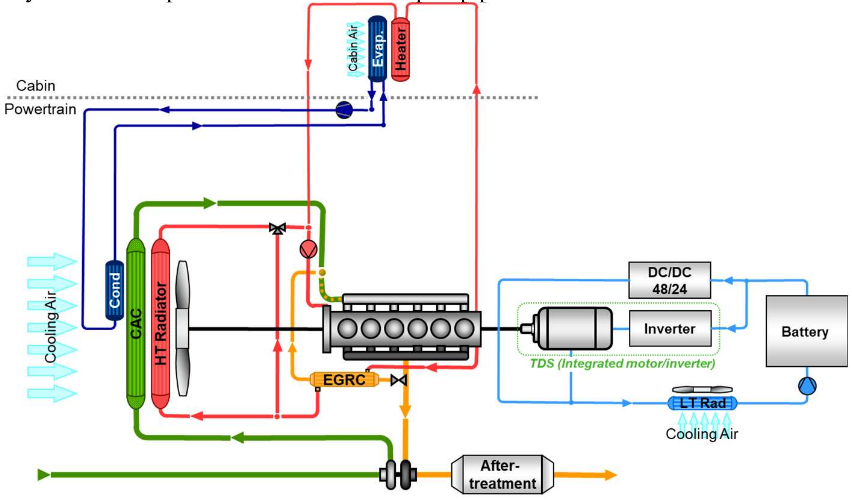

Fig. 8. Cooling system of an entry-level mild hybrid powertrain

In case the system power level gets increased by a stronger motor or by additional ancillaries, the coolant cooling of the battery may not be sufficient anymore. In this case an optional cooling of the battery with a chiller can be added.

Plug-in-Hybrid with pure electric driving capabilities (PHEV).

Pure electric driving capabilities may become mandatory in environmentally sensitive urban areas in the near future. A hybrid powertrain with pure electric driving capabilities may be a good combination to operate emission free in the city as well as going long distance with the diesel engine. This requires a powerful electric motor to conquer smaller hills and get satisfying accelerations at traffic lights, but there might be some limitations.

The battery size should be big enough to guarantee at least 50 km electric range. In addition, many ancillaries need to be electrified to guarantee a safe electric drive (air brake compressor, power steering pump, …).

The heat rejection of the electric drive components will hardly allow a front-end integration of the low temperature without compromising charge air cooling quality. That's why a remote module on the side of the vehicle is more favorable (Figure 9). This module contains two radiators: The first radiator is used for battery cooling at cool ambient conditions up to 15 to 20°C and the second radiator of the same size is used for electronics, e-motor and ancillaries. This split allows higher operating temperatures for the electronics loop, which supports heat transfer significantly. The temperature difference between battery inlet temperature and ambient can also be increased compared with mHEV system as the chiller will take over battery cooling in case battery inlet temperature gets too high.

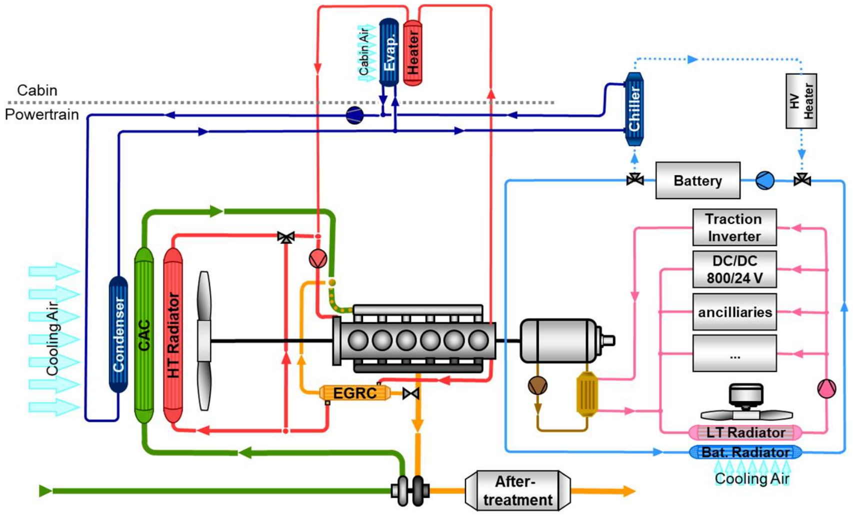

Fig. 9. Cooling system layout for a full hybrid powertrain

3.3 Battery Electric Powertrains

A typical layout for battery electric trucks is shown in Figure 10. It includes two coolant and one refrigerant circuit. The oil cooling of the traction motor is optional and depends on the type of traction motor chosen.

Like for the hybrid system, all electronics and traction components are allocated in the main low temperature circuit which guarantees coolant temperatures below 60°C. The battery has its own coolant circuit, which either can be cooled by a dedicated radiator or by a chiller. Both radiators are located in the front of the truck to use ram air for cooling and to minimize fan usage.

As the coolant temperature in the LT circuit is too low for cabin heating an additional high voltage heater is required. It can either be installed in the coolant circuit of the heater core or on the air side in the HVAC module. The air side integration is more efficient than the coolant side integration but requires changes on the HVAC module. This may be difficult if the same module is used as platform HVAC module for ICE and BEV applications.

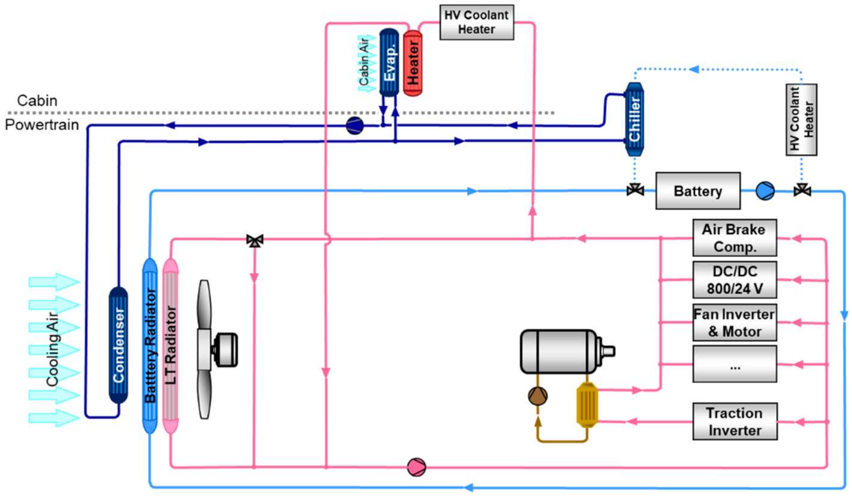

Fig. 10. Generic cooling system layout for a battery electric truck

Refrigerant Circuit Layout.

The layout shows a common refrigerant circuit for HVAC and battery cooling. Especially for high performance applications, the range from low to high heat loads may exceed the capabilities of some component as well as the limits of operation and controls of the system. As the vehicle must cover low load conditions like hotel modes in resting situations as peak power operation at hot ambient conditions the spread of the requirements for the different components might be too large. In these cases, it may be appropriate to separate the HVAC refrigerant loop from the battery cooling loop. This allows circuits which are more tailored to the actual needs of the individual subsystems.

Fast Charging.

Another feature, which may require to revise the refrigerant circuit are upcoming fast charging capabilities of battery electric trucks. The common narrative proposes to recharge the truck for the next 4,5 hours of driving during the mandatory breaks of the driver. So, depending on the vehicles weight and duty cycle, the battery has to store 300 to 600 kWh within 30 to 45 minutes. This is a charging power between. 600 and 800 kW. Some are actually talking about more than 1 MW [4]. This results in high battery heat loads which exceed the heat rejection during driving at peak power of more than 50%. Although the thermal inertia of the battery may help to cope with this challenge, it is expected that major components as chiller, compressor, condenser and cooling fan need to be upscaled significantly.

Braking Systems.

A critical function of a battery electric truck is braking. Today an independent endurance braking system in addition to the normal service brake is mandatory [5]. At least for smaller trucks with limited payload, regenerative braking is considered to be sufficient to fulfill the legal demands. For more heavy vehicles, especially for long haul trucks or trucks operated in the mountains, the desired braking performance of the driver/operator may exceed the possibilities of regenerative braking system, as they are used to powerful engine brakes and driveline retarders today. In this case the additional installation of brake resistors or even driveline retarder systems could be an option. The heat rejection from these systems is very high and require a high temperature heat sink, which needs to be integrated into the thermal management system and impacts radiator size and installed fan power significantly.

Fans.

BEV trucks need electrical fans for the main cooling module. As these trucks cover a wide range from medium duty distribution trucks to heavy duty long-haul, the electrical fan power required varies significantly depending on the vehicles specifications like motor power, gross vehicle weight, charging power and braking system installed.

For medium-duty distribution a typical fan power is between 2 and 5 kW. For a BEV heavy-duty long haul truck, the required fan power can exceed 30 kW.

Heat Pumps.

For battery electric cars, heat pump systems are an appropriate technology to reduce the negative impact on the vehicle range due to cabin heating under cold ambient conditions. But the gain in range depends on the ratio of traction power to heating power. From the viewpoint of the heat pump, this gets more and more unfavorable with increasing vehicle weight. Therefore, it needs to be further investigated, which benefit a heat pump can add on the driving range of a specific application.

The benefit may be different for medium duty distribution trucks, which get charged overnight in a depot. In this case the cooling system and the battery can be preconditioned so they can be used as heat source at least during the first hours of operation. In a case study for a 16t gross vehicle weight distribution truck with 200 km range the range loss due to heating was significantly reduced (Figure 11).

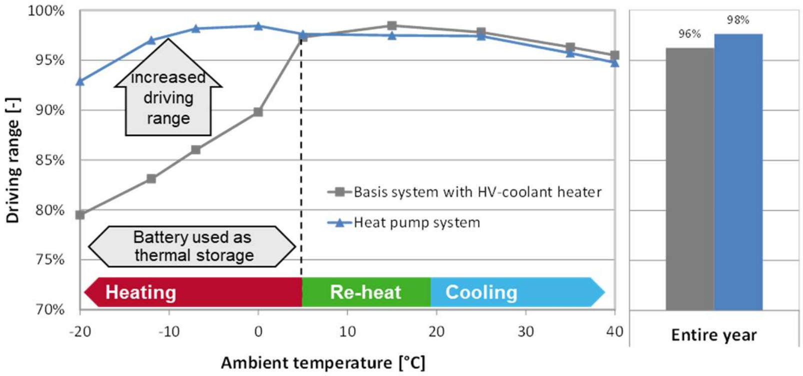

Fig. 11. Potential benefit of a heat pump system for a medium duty distribution truck (16t GVWR, 200 km range in urban driving, 200 kW traction motor power, battery as heat storage)

3.4 Fuel Cell Powertrains

Fuel cell powertrains are currently considered to be one solution for future sustainable road transport. As shown in chapter 2, fuel cell powertrains show a significantly higher heat rejection than the other options and are therefore a challenge for the design of the cooling system.

Figure 12 shows a generic layout of a fuel cell powertrain. The cooling system includes again 3 different cooling circuits. Instead of two low temperature circuits, there is now a low and a high temperature circuit.

The high temperature circuit is responsible for one or multiple fuel cell stacks. In addition, the charge air coolers and the hydrogen heaters of each stack are located in this cooling circuit.

The low temperature circuit hosts all components known from the battery electric powertrain and the electronic components from the fuel cell system (FC DC/DC, cathode compressor motor & electronics, …). The battery is incorporated into this circuit as a three-layer cooling module in the front end would be too difficult to package.

Remote Modules.

Due to the high heat rejection in combination with the high cooling air flow needs, it is necessary to add more frontal surface to the cooling system. Otherwise, the fan power will become excessive. Unfortunately, in the typical truck design the space in the front of the truck is limited and it will hardly be possible to package radiators significantly bigger than one square meter in this location. So, one or multiple remote modules need to be added. These additional modules can be located either on the side of the

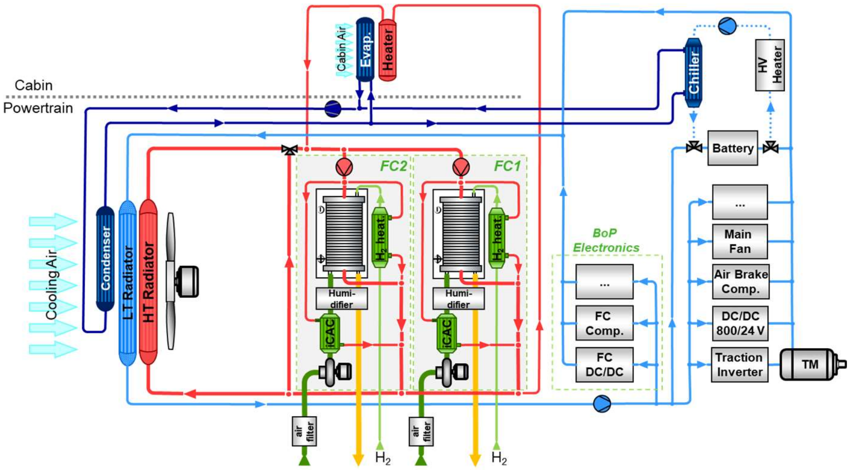

Fig. 12. Generic cooling system for a fuel cell powertrain with two fuel cell systems

truck, behind the cabin, or as fender module beside the front module. If these modules have to serve the low or the high temperature circuit depends on the available packaging space and the exact heat rejection rates of the actual application. As the remote modules typically have no or only little ram air support, electric fans in the range of 1 to 5 kW have to be installed on these modules.

Figure 13 shows the impact of additional remote modules for fuel cell cooling. The numbers reflect the fan power required for maintaining a coolant inlet temperature of 80°C to the fuel cell at peak power and an ambient temperature of 35°C. Each remote module has a size of 50 dm² and carries a 5 kW single fan.

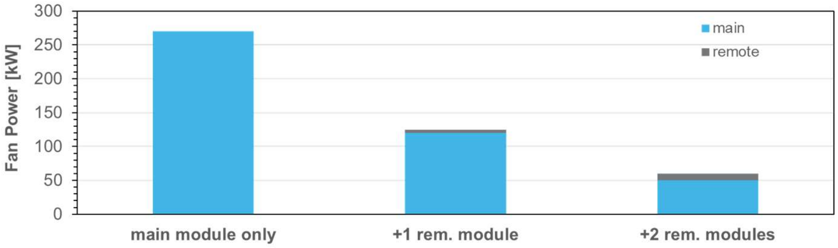

Fig. 13. Impact on fan power of additional remote modules for FC cooling at peak power, T_{amb}=35°C

Main Fan.

The main fan is a key element of fuel cell cooling. Due to its high power consumption, the efficiency of the fan is very important.

Today's fans for diesel ICE are optimized for delivering high air flows at low engine speeds. The power consumption at peak torque (n_{engine}=1100 rpm) is less than 10 kW and even at peak power (n_{engine}=1500 rpm) the fan power consumption is less than 15 kW. During engine braking, the fan is actuated at higher speeds and consumes then more than 40 kW.

In a fuel cell powertrain, the main fan is not connected to the drive train and is therefore electrically driven. This results in an additional degree of freedom for optimizing the fan blade. The new MAHLE fan generation provides a significantly higher efficiency. At the same air flow, the power consumption is reduced by more than 20% (figure 14).

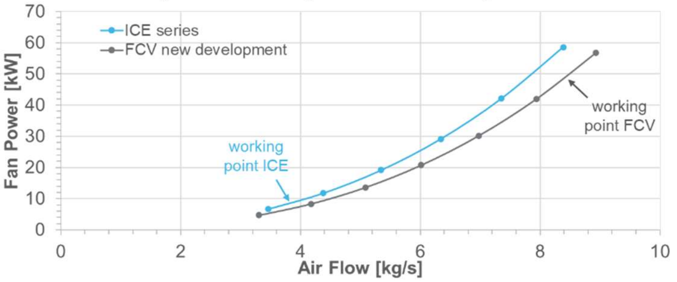

Fig. 14. Fan consumption vs. air flow for a MAHLE serial production and an optimized fan design for fuel cell applications.

Radiator.

An important aspect for fuel cell radiators is coolant-side cleanliness and low emission rates for ions. For safe operation and maintaining the necessary isolation resistance the fuel cell uses a low conductivity coolant. During operation, an ion exchanger is used to keep the conductivity low. To ensure a long service interval of this component and to avoid too high conductivity levels for new vehicles and after longer inactive periods, all components in the fuel cell cooling circuit must meet stringent specifications for ion emissions. Therefore, a special cleaning and passivation process was developed at MAHLE. This process can be used for all kind of heat exchangers inside the fuel cell coolant circuit.

4 Summary

For meeting future CO_2 legislation and making road transport more sustainable, a growing number of electrified trucks will be introduced. These trucks will use new powertrain options like hybrid, battery electric or fuel cell powertrains. With these new options, additional components like electronics, batteries or fuel cells will be added to the powertrain. Each of these components has individual needs for thermal management, which partially differ significantly from the still predominant ICE powertrains.

Therefore, the thermal management and the layout of the cooling system is a crucial part in the development process of the new powertrain options. To find the best thermal management system for each application, a thorough assessment of all involved heat sources is recommended. If possible, this should be carried out on an energy flow level. With these information and packaging envelopes for the heat sinks a cooling system can be laid out, which meets the thermal targets with the lowest possible power consumption of compressors, pumps and fans.

References

1. Lutz, R. Electrified trucks 2021, MAHLE internal report, 2021.
2. Banzhaf, M., Lutz, R.: Heat Exchanger for Cooled Exhaust Gas Recirculation, VTMS conference, SAE paper 971822, 1997
3. Lutz, R., Art, L. Haar, D.: Fuel Saving Potential of Indirect Charge Air Cooling for Heavy Duty Trucks, Baden-Baden Engine Congress 2017
4. Fraunhofer ISI: „Hochleistungsschnellladenetz für Elektro-Lkw“, Kurzstudie im Auftrag des Verbandes der Automobilindustrie (VDA), 29.5.2020, http://publica.fraunhofer.de/dokumente/N-608666.html
5. UN/ECE Regulation No. 13, rev. 8

Glossary for Diagrams

Abbreviations

BEV	Battery Electric Vehicle
EGR	Exhaust Gas Recirculation
FCV	Fuel Cell Vehicle
HEV	Hybrid Electric Vehicle
HT	High Temperature
HVAC	Heating, Ventilation, Air Conditioning
ICE	Internal Combustion Engine
LT	Low Temperature
PHEV	Plug-in Hybrid Electric Vehicle