Article citation info:
Stajuda L, Levchenko D, Kubiak P, Siczek K, Boguslawski G, Kuchar M et al. Composition, features, problems, and treatment related to cooling fluid – a review. Combustion Engines. 2024;196(1):106-125. https://doi.org/10.19206/CE-169185

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Combustion Engines
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Composition, features, problems, and treatment related to cooling fluid – a review

ARTICLE INFO

Received: 20 May 2023
Revised: 1 July 2023
Accepted: 3 July 2023
Available online: 6 July 2023

Vehicle coolant is one of the most important operating fluids. Along with changes in the design of engines, the composition of the coolant has also changed. The main function of the coolant is heat transfer (HT). It absorbs up to one-third of the heat energy generated by the engine. The coolant is also responsible for protecting the cooling system from damage caused by corrosion, scaling and deposits. The unfavorable working environment of the engine is also affected by smaller capacities of the cooling systems (CSs) of the drive units, extreme temperatures and increased pressure in the CS, enhancing the importance of the fluid composition. The coolant must be replaced every three years or 100,000 kilometers or every five years or 250,000 kilometers with the Organic Acid Technology (OAT). It is worth remembering that coolant of unknown composition or low quality used for a long time can expose the system to engine overheating, corrosion, deposits and restriction of liquid flow. This can lead to engine failure, in extreme cases even engine seizure. Currently, many types of fluids, including nanocoolants with different compositions, are available on the cooling market. The article presents these fluids, describe the most common failures of CSs, present the currently used methods of fluid replacement in the engine and proposes an innovative method based on the pressure method, which allows both replacing the fluid in the entire system and cleaning it.

Keywords: *combustion engine, hybrid and electric vehicles, cooling system, nanocoolant, device for coolant change*

1. Introduction

Recently, the development of internal combustion engines (ICEs) has been accompanied by the enhancement in their aggregate power strongly affected by their average effective pressure and speed, and the extensive use of electronic control units (ECUs). The mentioned engine power enhancement is accompanied by raised thermal and mechanical loads on the components of the engine systems. The high reliability of ICE needs the proper balance for the parameters of the fuel supply, pressurization, lubrication and cooling in an engine. The selection and provision of the needed parameters during engine operation are conducted by engine control systems linked to the onboard computer. The introduction of the new engine to the market, its modernization or even repair is accompanied by studies focused on improving automatic systems, devices and software for adjustment of the ICE thermal state and factors of engine cooling to provide their reliability with raising thermomechanical loads [179].

The ICE CS should ensure the best thermal state of its parts and assemblies. The operational engine temperature (ET) should be close to optimum, to allow retaining the material strength of engine components, very good lubricity and load-bearing ability of engine oil, and minimum heat loss via the CS [179].

About 70% of fuel energy is transferred and lost to the engine and vehicle CSs, the exhaust gas, and frictional parts [100]. The design of a CS of an ICE usually allows for removing as much heat as possible. A car's CS comprises two regions: the hot part and the cold part. The latter comprised zones where the coolant fluid quits the radiator and flows to the engine; the hot part comprised zones where the fluid quits the engine, after the heat deletion, and flows to the radiator [10].

The CS removes 30–35% of total heat [125]. Nowadays, the liquid- and air-CSs appear in vehicles. Most automobiles and trucks use liquid-CSs [161].

In an air-CS, the engine block is covered with a set of fins made of Al alloy (for example, AA204) conducting the heat away from the cylinder. A powerful fan forces airflow over the fins, cooling the engine by transferring the heat to the air [65].

The amount of such transferred heat is affected by the total area of the fin surfaces, the velocity/amount of the cooling air (0–25 m/s), and the temperature of both the fins (up to 72°C) and the cooling air (20–40°C) [65].

Air-cooling is mostly used in fewer horsepower engines, including motorcycles, scooters, small cars and small aircraft engines, the forward motion provides enough airflow (speed) to cool the engine. The air-CS is also applied in some small industrial engines [25].

It was noticed that the tendency to enhance the temperature level of ICE cooling [139, 145] and the ever-wider use of high-temperature CSs (HTCS) in diesel engines [27, 42, 120, 180]. The coolant temperature (CT) of the ICEs manufactured by MAN B&W Diesel Ltd, Caterpillar, General Motors, Wartsila/Sulzer, Deutz AG, Barnaultransmash OJSC ranged from 115 to 126°C [26].

Cupiał et al. [45] described a gas engine with a two-stage compressed mixture water cooler with an outer ventilator to cool down the compressed hot air-biogas mixture to a temperature of about 40°C before delivering it to the inlet manifold and the cylinders. This tubular-type cooler comprised tubes and a package of flat ribs made of copper.

Various electric and hybrid vehicles utilize electric motors (EMs) cooperating with various battery sets. They operate best under narrow temperature variations provided by cooling and heating systems [72]. Some of them utilize various coolants. The goal of the present paper was to review problems related to vehicle liquid fluid-based CSs.

2. Cooling systems of electric and hybrid vehicles

The electric car battery can be cooled with phase change material (PCM), fins, air, or a liquid fluid [49]. Chen et al. [37] considered four battery-cooling methods: air-based, direct liquid-based, indirect liquid-based, and fin-based.

PCM absorbs much heat energy by modifying the state from solid to liquid under little temperature change. Application of such materials is limited due to the volume change occurring at a phase change (PC), pure absorption without transferring of the heat generated away, which slows down limiting overall temperature compared to other systems [49]. Several studies were conducted on PCM-based CSs [67, 102, 166, 177] comparing battery and PC cold storage in a PV CS in various climates. PCMs are unfavorable for use in vehicles but can lower internal temperature fluctuations and peak cooling loads, improving thermal performance (TP) in buildings or infrastructure devices, such as battery rooms, power supply stations, or so-called energy tanks [49].

Cooling fins have high surface area to increase the HT rate from the battery pack (BP) to them, then to the atmosphere. The fins are used in electronics and additional CSs on ICE vehicles. However, they are inefficient for the electric car battery sets due to the fins weight outweighing the profits from their high thermal conductivity (TC) [49].

Air cooling (AC) transfers heat from the BP to air running over its surface. AC appeared in earlier electric cars like the Nissan Leaf. Despite, its simplicity and easiness, AC is not efficient compared to liquid cooling (LC), causing safety issues in hot climates [49]. Several studies were conducted on ACs [38–41, 54, 73, 108, 109, 171].

Liquid coolants possess better TC and heat capacity than air, compact structure, and ease of arrangement. They best ensure the correct temperature range and uniformity of a BP. LCs cause safety problems relevant to leaking and disposal under improper coolant (glycol) handling. They currently appear in Tesla, Jaguar, and BMW, to name a few [49]. Several studies were conducted on LCs.

Chen et al. [37] reported that an air-based CS needed up to 3 more energy than others to provide the same temperature. An indirect liquid-based one exhibited the lowest maximum temperature rise. A fin-base one rose by 40% in weight of the heaviest battery when the four kinds of CSs were of the same volume. Indirect liquid-based one was more usable than a direct liquid-based one despite its slightly lower cooling efficiency.

Huang et al. [76] stated that EMs in hybrid electric vehicles (HEVs) generate considerable heat depending on the operating conditions. Thus, an effective motor CS is needed to keep the temperature within a prescribed range. The classical coolant-based system is efficient but spends energy on driving the coolant pump and radiator fan. The authors studied a hybrid CS linking heat pipes with conventional coolant in a compact thermal cradle. Such a system allowed heat removal via an integrated thermal pathway by regulating centrifugal fans, radiator pumps, and fans to minimize energy use. The EM temperature was maintained close to the 70°C. Additionally, a higher energy amount was saved than in case of a conventional LC systems.

Operation of an EV with high effectiveness needs maintaining the best temperature range for the EM, the power electronics and the BP. This is realized with a thermal management (TM) system using:

- a refrigerant-based system consisting of a condenser, evaporator and an unit comprising battery cells, cooling plate and electric auxiliary heater. It utilizes the refrigerant from the air-conditioning system (ACS) and is managed apart via valves and temperature sensors.
- coolant and refrigerant-based flow-path subdivided into several sections, each comprising an individual low-temperature cooler, a coolant pump, a thermostat and a coolant stop valve. The refrigerant flow-path of the ACS is also linked via a chiller. A HV coolant heater allows proper battery temperature management at low external temperatures.

The CT for the EM and the power electronics is kept under 60°C inside an individual flow-path via a low-temperature cooler. The CT of the battery should be in the range of 15–30°C. At too-low temperatures, the coolant is warmed via an auxiliary HV heater. At too-high temperatures, it is cooled via a low-temperature cooler. When necessary, a chiller linked into both the coolant and refrigerant paths further lowers the CT. The refrigerant of the ACS passes via the chiller, further cooling down the coolant also passing via the chiller. The control is realized via separate thermostats, sensors, pumps and valves.

The ACS operation inside the vehicle is affected by the engine operation because of the mechanically driven compressor with a belt from the engine. When the engine stops, the temperature at the evaporator outlet of the ACS rises after just 2 seconds. The accompanied low rise in the temperature of the air blown in by the ventilation and the humidity rise is nasty for passengers. To avert low temperatures of accumulators, so-called storage evaporators comprising an evaporator and an accumulator block are used. The refrigerant passes via both blocks in the start-up phase or the engine running. Meanwhile, a latent fluid in the evaporator is chilled up to freezing. When the engine stops the warm air passing via the evaporator cools down, and a heat exchange (HX) occurs until full melting of the latent fluid. Once the vehicle carries on the process repeats [72].

Three temperature management options are used [72]:

Option 1 – air is drawn in from the air-conditioned vehicle interior and cools the battery. The cool air extracted from the vehicle interior has a temperature below 40°C. This air circulates around the accessible surfaces of the BP.

Option 2 – a specialized evaporator plate inside the battery is linked to the vehicle ACS using the decomposition process on the high-pressure and low-pressure side via pipelines and an expansion valve. The evaporator inside the vehicle and the battery evaporator plate are linked to the same flow-path. While the interior CS contains the comfort requests, the HV battery should be chilled with various intensities according to the driving situation and the ambient temperature. The particular design of the evaporator plate and its linking to the battery provide a great contact surface for the HX. This prevents reaching the temperature above 40°C. Evaporator plates directly linked to the battery are not separately replaceable. Their damage needs the battery exchange.

Option 3 – to enable additional heating at very low temperatures, the battery is linked into a secondary flow-path, ensuring maintaining the operating temperature in the range of 15–30°C at all times. Coolant (water/glycol blend) passes via a cooling plate linked to the battery block. At lower temperatures, the coolant is quickly warmed by a heater. The latter is shut off if the temperature in the battery increases under the use of the hybrid functions. The coolant is then chilled via a battery cooler in the vehicle's front end or a low-temperature cooler using the airstream from the vehicle driving.

At high external temperatures, the coolant passes via a HX unit. Therein, refrigerant from the vehicle ACS is evaporated. The heat is delivered from the secondary flow-path to the evaporating refrigerant. An additional re-chilling of the coolant is executed [72].

Due to high cooling effectiveness, compact structure and flexible geometry, heat pipes were applied in various cooling systems of the EV battery CS [57, 78, 103, 164]. Zhao et al. [176] studied the TP of a mini-channel liquid-cooled cylinder for cylindrical power Li-ion battery (LIB) affected by channel quantities, mass flow rate, flow direction and entrance size. Zhang et al. [174] studied temperature distributions for the BP with liquid flow in the cooling process. Saw et al. [138] investigated the open cell Al foams forms with various porosity for the LIB CS. Xu et al. [172] studied the mini-channel cooling preventing thermal runaway of the LIBs. De Vita et al. [47] investigated the influence of various CSs on the transient thermal behavior of the LIB pack. Al-Zareer et al. [11–14] elaborated a TM system using boiling cooling for high-powered LIB packs for HEV. Bai et al. [23] studied the TM performance of the PCM/water cooling plate used for the LIB module. Rao et al. [127] investigated the influence of variable contact surface on the liquid TP of the cylindrical LIB module. Deng et al. [46] tested the cooling effectiveness of the power LIB with various coolants and cooling manners. Wang et al. [165] studied a forced gas cooling flow-path packaging with a liquid plate for the TM of LIBs. Tan et al. [123, 151] elaborated the carbon-fiber composites with 2D microvascular panels for battery cooling (BC). Jiaqiang et al. [89] tested the effect of LC structure on the cooling effect in battery thermal management (BTM) system. Tian et al. [155] studied the integrated TM system with BC and motor waste heat recovery for EV. Zhao et al. [175] studied the thermal behavior of discharging/charging cylindrical LIB module cooled by channeled liquid flow. Shahid and Chaab [143, 167] developed a technique to improve air-cooling and temperature uniformity in a BP for cylindrical batteries and hybrid cooling. Gillet et al. [64] tested an automotive multi-evaporator ACS and battery CS. Li et al. [96] studied the water-cooling-based strategy for LIB pack dynamic cycling for the TM system. Malik et al. [111] tested the TP and electrical performance of the set of LIBs with LC.

There are several Thermal Management (TM) approaches used to control and limit the temperature offset for high voltage (HV) BPs applied in HEVs end EVs dependent on the heat transfer (HT) medium used: air [110, 173], liquid or PCM [8, 9, 92, 101, 116]. The choice of the transfer medium is a trade-off between vehicle topology, performance, durability and costs.

In the case of Plug-in Hybrid Electric Vehicles (PHEVs), only PCM is inapplicable [92] and often either AC or LC is needed. While AC systems are simpler and cheaper, LC ones offer higher efficiency in HT and higher precision in temperature adjustment [122]. The complex liquid CSs with intricate pipe architecture utilize a TM control way that engaged the numerous electrical pumps, valves and fans to keep the battery sets within the best operation range, spending minimum electrical energy [106, 107, 113, 178].

Interestingly, Catuneanu et al. [33] reported the existence of a practical thermal limit to traditional Intelligent power modules within electric vehicle (EV IPM) HX units. Thus, the traditional LC strategies can be insufficient to cool the next generation of EV IPMs as semiconductor technology transitions from Si IGBTs, to SiC MOSFETs and GaN power HEMTs, with progressively decreasing die areas. However, until now, no violations of this thermal limit have been noticed.

Vijaya et al. [162] developed a battery monitoring and management system to control the temperature, voltage, current, charge and discharge cycle of LIB sets in EVs. Such a system possesses a liquid CS with a coolant tube inserted between battery cells to cool them when overheated.

Ayers et al. [22] elaborated a CS for the power electronics of HEVs. A common automotive refrigerant R-134a (1,1,1,2 tetrafluoroethane) is applied as the coolant in a system that can be used as either part of the existing car ACS or independently of the existing air conditioner.

The cooling of the vehicle's battery set can also be realized using nanocoolant (NC). Wiriyasart et al. [168] studied the temperature distribution and pressure drop (PD) using NCs flowing in the corrugated mini-channel of the EV BC module. They found that temperature distributions in the module are strongly affected by the flow direction, mass flow rate, and types of coolant. Using NC allowed a reduction of 28% of the maximum temperature compared to the typical cooling module. However, the PDs also enhanced. The NCs provided a cooling capacity greater than that of water.

Summarizing, one can note that various systems for cooling HV BPs in HEV and EVs are under development. Various coolants like water, EG or their mixtures, and others, including NCs are applied to them. Also, various TM approaches are under development.

3. Cooling systems of vehicles with ICEs

In the liquid-cooled ICE, coolant fills a CS and acts as a HX fluid. It flows only within the cooling circuit via rubber hoses from the radiator to the engine. It does not appear in air-cooled engines [147].

According to [100], the engine CS (ECS) should keep the engine operating at the best temperature with the minimal fuel consumption. The radiator design should provide compactness and low PD and costs.

According to [135], there are two types of modern ECSs:

- pump circulation system – in this arrangement, a coolant circulates efficiently from the cylinder block to the radiator and back using a centrifugal pump driven by the engine v-belt or electric pump operating a part of the engine.
- pressurized CS – it is an amelioration over the pump circulation system of cooling. Such a system comprises a special radiator cap having a spring-loaded pressure valve and a vacuum valve.

The cap is gas-tight, so when the engine is heated, coolant vapor is formed, which cannot go out. Therefore, the boiling point of water in the system is enhanced so the engine operating temperature also increases, providing higher thermal efficacy.

The pressure valve opens when the pressure in the system surpasses a certain predetermined value (often 0.05 MPa), allowing the steam to escape, preventing undue pressure formation. When the engine is chilled the vacuum valve opens and compensates for the loss of coolant or air.

The scheme of the ECS similar to the one of those described in [28] is presented in Fig. 1.

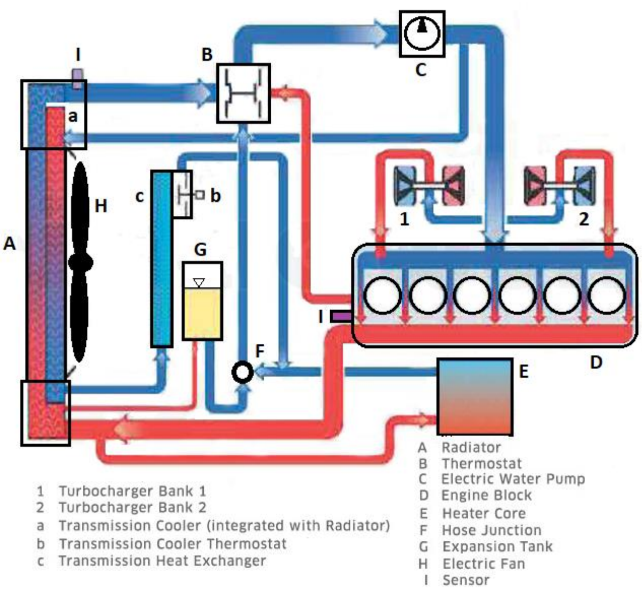

Fig. 1. The scheme of the ECS

Romero-Piedrahita et al. [131] stated that CS regulates ET within a prescribed range. This system facilitates the engine reaches the temperature quickly and evenly. Under cool weather, the CS should not over-perform as cold engines wear more rapidly, pullulate more, exhibit worsen fuel economy, and produce less power. Under-performing systems are prone to failures including burst hoses and warped metallic components. The too-cool engine operation worsens the passenger comfort in cool weather, while the too-hot one causes discomfort on warm days. However, for a better combustion performance achieving a very consistent operating temperature is beneficial. CS performance is somewhat proportional to engine power, so improving the engine requires enhancing the capacity of the CS. The ECS layout is particular for each application and is mainly determined by the engine warm-up strategies as well as the position of the heater core, oil cooler, and EGR cooler in the branches of the CS. The coolant is driven to the engine water jacket by the action of the coolant pump. At the exit of the engine, the coolant is conveyed to the water box, from which the flow is diverted through four branches connected in parallel: to the radiator (as the thermostat opens with the CT increase), to the expansion tank, to the heater core, and to the bypass, which is the shortest way to the engine inlet.

Additives comprised in coolant protect the CS against corrosion, cavitation and scaling. The blending of inconsistent coolants causes the additives to "drop out" of the solution and form radiator sludge or slime. A failed head gasket or cracked cylinder head allows oil and coolant to blend, also causing a sludge. In vehicles with automatic transmissions, where the ECS also cools the transmission, failure of such a system contaminates coolant with transmission fluid. When an imbalanced coolant chemically reacts with metallic surfaces causes corrosion, forming reddish deposits appearing as sludge or slime [16].

According to [125], a CS comprises above ten devices and parts presented further in the chapter and Fig. 1.

The temperature of the engine coolant (EC) is checked with Coolant Temperature Sensor (CTS). The signal from this sensor is utilized by the ECU to regulate fuel injection and ignition time. Some engines have numerous CTSs, while some have just one. The signal from CTS is also used to control the radiator fan and update the driver console's temperature gauge. Most CTSs are of the negative temperature coefficient type with resistance decreasing with the temperature rise. The CTS can have a two- or three-pin type, depending on the vehicle [53]. The sensor must stay in a specific resistance range to satisfy the computer operating program. If such values are out of range the computer turns the engine check procedure on and produced a trouble code pointing to a needed sensor replacement [180]. The CTS is a high failure item needing replacement when decreased fuel mileage, engine overheating, reduced engine power, or backfires appear [181].

The radiator core is produced from flattened Al tubes with Al strips/fins arranged in zigzag mode betwixt the tubes. The fins shift the heat from the tubes into the air stream carried out to the atmosphere. On each end of the radiator core, there is a plastic reservoir covering the radiator ends. The tubes can be arranged horizontally with the plastic reservoir on either side or vertically with the reservoir on the top and bottom. On radiators with plastic end caps, the gaskets between the Al core and the plastic reservoirs seal the system and prevent coolant leaks [10, 53].

A crack or leak from the radiator can lead to a significant loss of coolant or antifreeze. Without these fluids in the CS, air bubbles start developing [75].

One or two electric cooling fans within a housing, which protects fingers and directs the airflow are positioned on the back of the radiator on the side nearest to the engine. These fans keep the airflow via the radiator under automobile slow driving or stoppage with the engine operating [10, 53].

The radiator fan defect is often caused by wear and tear, compromising bearings. Much deteriorated bearings induce a fan improper operation. An EM fan assembly is eager to fatigue as well. Sometimes, a radiator fan can become non-active when struck by debris from the road. It also happens that a wrong motor mounting causes a slight engine tilt was leading the fan blades to hit surrounding vehicle components [30].

A bad or failing cooling fan motor displays symptoms:

- cooling fans do not turn on due to the cooling fan motors burning out or failing,
- the cooling fan motors failing allows the rise of the ET until the engine overheats,
- a blowing cooling fan circuit fuse occurs when the motors fail or surge, to protect the rest of the system from any sort of damage due to electrical surges. The fuse replacement usually allows restoring functionality to the fans [132]. However, faulty relays and damaged wiring also prevent motor operation. The long-term lack of the noise of a radiator fan motor usually hearable within a few seconds after an engagement, can signal motor malfunctions [30].

As a radiator fan also sucks air via the HVAC (heating, ventilation, air conditioning) system's A/C (air/conditionning) condenser, an ineffective fan causes an inadequate cabin chilling. This issue occurs especially at slow vehicle speeds, as condenser airflow is highly restricted [30].

The unforeseen turn on a car's temperature warning light can indicate the cooling fan's fault due to a non-enough airflow in the radiator leading to overheating. Sometimes, coolant can boil signaled by steam coming from beneath the radiator [30].

A reservoir tank prevents coolant cavitation at too high engine speed, causing unstable CS pressure, leading to system overheating or damage. It maintains high radiator efficiency and control CS pressure, thus preventing temperature rises [117]. Thick white smoke emanating from the exhaust pipe indicates low antifreeze levels in the coolant reservoir [75].

The radiator pressure cap maintains pressure in the CS up to a certain value. If the pressure exceeds such a set value, it is released by a calibrated spring-loaded valve [10]. A faulty pressure cap is signaled by coolant leaks, a reservoir overflowing, a radiator hose collapse, the air in the CS, and engine overheating [21].

A water/coolant pump keeps the coolant circulation as long as the engine operates and is affixed on the engine front. The pump can be driven by the engine via:

- a fan belt driving an alternator or power steering pump;
- a serpentine belt driving the alternator, power steering pump or/and AC;
- the timing belt driving one or more camshafts [125].

Coolant pumps withstand varying temperatures (–40°C to 120°C), speeds (500–8000 rpm) and pressures of up to 3 bars, thus requiring high bearing and sealing resistance. The mechanical pump comprises the drive wheel and impeller made of plastic and metal installed on a common shaft mechanically sealed towards the outside. The rotating impeller drives continuous coolant circulation within the CS. The coolant provides lubrication and cooling of the shaft mechanical seal. The shaft bearing strain is lower with plastic wheels not too liable to cavitation. However, plastic wheels become brittle over time. Due to design limits, small amounts of coolant can reach the free space after the sealing ring and escape at the pump's relief bore [72].

The electric one and its integrated electronic control operate independently of the engine and as required. Not initially running under a cold start, allows the engine to achieve its operating temperature faster. Even at idle or stopping the engine, the electric pump provides adequate cooling power. This lowers power consumption, friction losses and fuel consumption, thus reducing engine emissions [72].

The brushless electric pump is installed separately and out of the engine. It is lightsome and maintenance-free. At a voltage of 12–360 volts, it achieves outputs of 15 to 1000 watts. Coolant lowers the temperature of the pump's EM. Using a pulse-width modulated (PWM) signal, its flexible control facilitates keeping the cooling temperature constant. According to the drive type (ICE, hybrid, electric) and the system, one or many pumps can be applied [72].

Vehicles with diesel engines can lower their fuel consumption using the 48 V technology, particularly a 48 V motor, to propel the coolant pump on a 13-L diesel engine applied in the commercial vehicle class [91].

Low pressure in the CS strongly affects the operation of the pump. This is usually caused by a faulty radiator pressure cap, leaking hose, clogged radiator, compromised seals, and low fluid levels [149].

A coolant pump failure can be accompanied by noise, loss of coolant, poor cooling and engine overheats. Such failure can be caused by electrical damage (short circuit/interruption) or/and mechanical damages including impeller lose or breaking, defects of bearing or seal, drive wheel damage, canal cross-section constricting because of corrosion or sealant cavitation, impeller failure resulting from creation or decay of steam bubbles in the coolant [72].

The drive wheel damage or loose drive wheel ring is caused by the too high strain of the timing belt or its insufficient orientation. The broken pump bearing, or its cage is induced by intensive oscillations caused by a defective Visco clutch. Coolant leakage results from worn-out or cracked seals. Sealant mass residues can enter the cooling circuit and injure the slide ring seal. Corrosion in the whole CS can result from faulty cylinder head sealing allowing engine emissions to reach the CS. The wrong pH value of coolant also facilitates corrosion development. The impeller, housing, slide ring seal and shaft can be seriously injured by pinholing caused by the action of old coolant with a significant quantity of chlorides under higher temperatures. Excessive coolant leakage at discharge boring can be induced by corrosion in the CS [72]. Incorrect coolant water mixture or contaminated coolant can cause deposits in the water pump [149].

Huang et al. [77] stated that the limited engine radiator volume leads to excessive coolant flow resistance making engine water pumps inclined to cavitation. Accordingly, air bubbles easily permeate into the EG, highly lowering the performance, reliability and service life of the engines. The authors studied the effects of the EG amount in coolant in the engine water pump on the coolant-supply capability and cavitation temperature at the occurrence of air or burnt gas in the system. They found that engines exhibit a higher tolerance to air bubbles at lower speeds. At a fixed speed, the tolerable cavitation temperature of an engine's water pump fell slowly with enhancing of the quantity of air bubbles.

The thermostat has two main functions [131]:

- restricting the coolant flow to the radiator at low operating temperatures,
- keeping CTs within pre-defined limits.

The thermostat is a valve controlling the CT. If warm fairly, it opens allowing the coolant to pass via the radiator. In the contrary case, the passing via the radiator is locked, and the coolant is guided to a bypass system allowing the coolant to return directly to the engine. The bypass system keeps the coolant flow via the engine to equalize the temperature and exclude hot points. As passing via the radiator is locked, the engine reaches operating temperature faster and, on a chilly day, allows the heater to start pressing hot air into the interior faster. Thermostats keep the temperature of the coolant in a range from 192 to 195 degrees. The engine operation at such hotter temperatures lowered emissions. Additionally, moisture condensation within the engine is fast incinerated prolonging engine life and allowing an entire combustion increasing fuel saving. The thermostat comprises a sealed Cu cup containing wax and a metal pellet. When the thermostat warms up, the hot wax broadens, shoving a piston against spring pressure to unlock the valve and allow coolant circulation. The thermostat is often positioned on the engine front top in a coolant outlet housing ,also the linking point for the upper radiator hose. The thermostat housing is joined to the engine with pair of bolts and a gasket sealing it against coolant escapes [125].

Various configurations of thermostats are available on the market. For example, Valeo offers three main thermostat types: conventional wax thermostats with pre-defined opening temperature, electrically heated wax thermostats with variable opening temperature and quick responding due to optional current feed, electrically actuated thermostats allowing full control of the CS independently of CT [157].

The failing thermostat can be marked by various symptoms including overheating or overcooling, coolant leaking, irregular temperature changes, strange sounds and heater problems [71], rust and deposit build-up, and inefficient engine running [48].

The bypass system allows the coolant to bypass the radiator and return to the engine. Some engines utilize a rubber hose or a fixed steel tube. The other uses a cast-in passage built into the water/coolant pump or front housing. When the thermostat is shut, coolant is guided to the bypass and back to the water/coolant pump, sending the coolant back into the engine omitting cooling by the radiator [125]. When an O-ring or gasket sealing the bypass tube to the engine wear out or tear, coolant leaking from the bypass tube producing a coolant smell from the vehicle's engine bay. The bypass tube can leak also due to excessive corrosion. The coolant bypass tube failure can induce engine overheating and serious engine injury [133]. A bad bypass valve is indicated by a coolant leak, engine overheating and electronic fails. The latter appears if software problems lead to the bypass valve malfunction. If so, the check engine light illuminates and persists until the problem disappears [160].

During the manufacturing of an engine block, a special sand sculpture maps the configuration of the coolant passages therein. This sand sculpture is located within a mold and then washed with molten metal (cast iron or Al alloy) in a casting process. Such a metal fills the space between the mentioned sand sculpture and the walls of the hole made in the molding sand previously thickened by churning in the casting mold. After the cooled metal maps the shape of the engine block, the sand is unfastened and taken out via holes in the engine block casting letting be the passages that the coolant passes via. Such passages should be closed using so-called freeze plugs [53, 125].

The machined flat mating surfaces between the engine block and one- or two-cylinder heads are sealed with the head gasket. Sometimes, additional gasket seals similar surfaces between the engine block and inlet manifold. The mentioned gaskets possess holes allowing coolant flow in the CS and preventing its leaks [53, 125]. In the case of a damaged, cracked, or weakened head gasket, antifreeze liquid leak and air bubbles develop leading to rapid overheating and other serious engine issues [75].

Providing needed heat to the vehicle interior is realized using the hot coolant flowing via a heater core linked to the CS with a pair of rubber hoses. One hose guides hot coolant from the water pump to the heater core and the other one gives the coolant back to the engine top [53, 125].

A set of several rubber hoses connects the components of the CS. The main hoses are called the upper and lower radiator hoses. Such two hoses are about 2 inches in diameter and direct coolant between the engine and the radiator [53, 125]. Over time, the hoses grow weaker or may develop cracks and holes resulting in coolant leaks [75].

White exhaust is related to leaks in your CS, which in turn causes the coolant fluid to get burned up by extremely high temperatures [75].

Various CSs including ECS, EGR coolers, air conditioning, frictional components (brakes, gearbox and bearings) CS, and electronic equipment CS were discussed in [100], mainly regarding minimizing fuel consumption.

Absorption cooling allows the effective reusing of the exhaust gas energy to drive the ACS for the compartment. However, the coefficient of performance (COP) of the absorption cooling is very weak.

Electronic CSs play an important role in electric/hybrid vehicles. However, some electronic equipment components operate under very low temperatures. For example, the operating temperature of a battery is below 55°C. Therefore, some new cooling manners need to be applied including PCM as a coolant in the battery CS.

With enhancing vehicle power, much heat produced in the frictional elements can be transferred to the atmosphere only with a separate CS.

The design of the ECS is strongly affected by the enhancing power and the space limitation in cars. Especially radiator dimensions should be optimized to provide more heat removed from the engine within limited space within a car.

To summarize, CSs become more and more complex with the development of vehicles due to the necessity of minimizing fuel consumption, reduction of exhaust gases and negative influence on the environment in case of coolant leaks.

4. Coolant types

4.1. Battery and power electronic (PE) coolants

Many innovative solutions related to hybrid and electric vehicles have been introduced on the market. Some of them need intensive cooling of electric/electronic components.

Coolants for HEVs, PHEVs, and battery electric vehicles (BEVs) are typically the same coolants used in the ICE. One should use a new, pre-mixed 50/50 coolant upon refilling the CS. In the contrary case, there can occur:

- cooling fin corrosion inside the heat-generating PE components causing low heatsink performance, overheating, and even failure,
- restricted passages inside the HV BC/heating plates causing overheating, setting Diagnostic Trouble Codes (DTC), and HV system shutdown,
- loss of HV isolation at a battery coolant heater element, causing DTCs and HV system shutdown.

The coolant should be replaced:

- the pink-colored Toyota Super Long-Life Coolant (SLLC) in the:
- ICE, every 10 years or 160,000 km and then every 5 years or 80,000 km afterward.
- PE, every 15 years or 240,000 km and then every 5 years or 80,000 km afterward.
- the orange-colored General Motors (GM) DEX-COOL every 5 years or 241,400 km.
- the blue-colored premixed Nissan Long Life Coolant used in their BEVs every 15 years or 200,000 km.
- the purple-colored Tesla G-48 ethylene-glycol Hybrid Organic Acid Technology (HOAT) coolant in their BEVs should be replaced every eight years or 160,000 km.

The coolant most often applied in engines is a blend of water with an antifreeze (usually ethylene glycol – EG). Such antifreeze prevents water from freezing in cold climates and increases the fluid's boiling point [10].

4.2. Classic coolants for vehicles with ICEs

When ICE generates the power necessary to overcome the vehicle’s resistance to motion, a high amount of energy is wasted as heat. The latter should be extracted from the engine mechanisms end efficiently transferred to the outside air and dissipated therein. This is usually done using different coolants, despite their low convective HT rates. An ideal coolant should exhibit small viscosity, great thermal capacity, chemical inactivity and cheapness [124], additionally without causing or promoting corrosion of the CS.

In the early state, ICEs were cooled with water with a very high specific heat value, high boiling temperature and low cost. However, a water freezing temperature of 0°C excluded it from engines utilized in cold climate zones. The water within a radiator expanded during the freezing process can destroy any water-only chilled ICEs in winter. Water also promotes corrosion generating metal oxides or rust with the materials applied in engines and radiators [43].

Although branded engine coolants (BEC) allow for mitigating problems related to elevated freezing point, low boiling point, inadequate pH and high corrodent effect of water, many drivers still apply water for chilling engines [152].

To prevent the results of coolant freezing, the methyl alcohol (methanol) can be blended with water and hence reduce its freezing temperature. However, such an antifreeze also reduces the boiling temperature of the water, which boils at 100°C. Engines reach operating temperatures at or over the 100°C and can readily boil water. The reduced boiling point of adopting methanol for antifreeze was thus unaccepted [43].

The next antifreeze generation was based on glycerol. It reduced the freezing temperature of the water but with enough efficiency down to only –37.8°C. It was not quite low enough for some winter climate conditions [43].

Next EG-based coolant generation became the new antifreeze of choice for ICEs. EG has almost one-half the specific heat value of water. When blended with water the heat portion retainable by a unit volume of such a blend is weakened. Such blends need to circulate more intensively to carry the similar heat portion that water alone would do. It is cheaper to produce, has a slightly higher boiling and flash point, and has a lower viscosity than propylene glycol (PG). Its freezing point is lower than that of PG and is around –11.5°C. It crystallizes at low temperatures and has a lower heat absorption capacity than PG. As EG is diluted, its freezing point decreases. Therefore, it is mixed with water [105].

The next coolant generation was PG-based, well adapted to automotive coolant purposes and non-toxic in moderate amounts. However, when included in coolant blends, it is eager to expand bacterial and fungal growth gradually, which can be limited by special additives [43]. PG is more expensive than EG, but less toxic, and does not crystallize, but thickens with decreasing temperature until it does not flow at all. It is less commonly used than EG. The lowest possible freezing point is achieved with a 68% glycol content in the water. Exceeding this value in either direction increases the freezing point [105].

Also, the chemical, glycerol, has recently been considered as a possible non-toxic replacement for EG [43].

Hull et al. [79] and Canter [32] noticed that engine coolants often include EG (1,2 ethanediol) or PG (1,2 propanediol). Such compounds have been the cheapest chemical bases for engine antifreeze/coolants for a long time [50].

According to [20] ECs comprised mainly: glycol (EG or PG), deionized water, and corrosion inhibitors. The features of ECs were strongly affected by the quality of each component.

The glycols in coolant mainly protect against freeze, albeit water gives the best HT [62].

FAL [61] reported that antifreeze solutions in automobile coolants typically have an EG content of 50%.

EG is more widely used in coolant than PG [128]. It has a lower viscosity, higher density, and better TC. However, despite its environmental benefit, PG is very expensive.

The coolants must effectively withstand high temperatures. Pure glycols can withstand over 180°C before boiling. Standard coolants can withstand 105 to 110°C. Adding a small amount of glycol slightly rises the boiling point [105].

Fuel Cell Electric (FCEV) and battery electric vehicle need low conductivity coolants designed for use with passivated HX units. When utilized in systems with un-passivated heat exchanges the coolant conductivity can vary during vehicle operation. It can be applied GuardIon coolant with low initial conductivity below 5 μS (microsiemens). Such coolant is diluted in a 50/50 proportion and cannot be blended with other antifreeze/coolants. The use of such a coolant provides freeze and anti-boil protection together with general corrosion protection in contact with aluminum, steel, copper, and brass surfaces [58].

Antifreeze producers utilize their own additives to enhance antifreeze life, greatly diminish corrosion, increase water pump efficiency and reduce foaming. Commonly antifreeze comprises a corrosion inhibitor, tolyl triazole, facilitating the detection of antifreeze leaks by smelling [43].

Corrosiveness is affected by the concentration of corrosive ions, such as chloride and sulfate [163].

Coolants comprise various additives called corrosion inhibitors, which inhibit corrosion and scale formation in the ECS [3, 34, 36, 150].

According to [68], corrosion inhibitors belong to general classes, like phosphates, silicates, and organic acids.

Coolant additives may comprise organic acids, silicates and phosphates, nitrites, defoamers, and bittering agents. Penrite Green OEM Coolant is recommended for vehicles with electric drivetrains systems for use in either the ICE CS or the BTM system in an electric-powered vehicle [121].

Li [97] also reported that silicates and phosphates are extensively utilized inhibitors. Jointly with molybdates and tungstates, they form the inhibitors reported in lots of recent patents [136]. Such inhibitors [5], including borates [44], are from inorganic sources.

Both organic and inorganic compounds are extensively utilized as corrosion inhibitors. Many inorganic compounds are poisonous and environment-unfriendly; thus, strictly limiting their application as corrosion inhibitors due to enhanced ecological awareness and strict environmental regulations. Many organic compounds get activated when adsorbed on the metallic surface [142]. Organic products like carboxylates are the main components in the additive package of Organic Acid Technology (OAT) coolants [18].

4.2.1. Ongoing use of various antifreeze/coolant types

It is necessary to choose from full-strength antifreeze or a 50–50 blend of antifreeze and water. The former needs blending with distilled water before introducing it into the ECS. A 50/50 blend operates for cold climates securing against freezing down to –37.2°C. A 60/40 blend of antifreeze to water for excessive cold can secure reduced temperature freeze protection [43].

Blending antifreeze with tap water is forbidden due to dissolved chemicals and/or chlorine can seriously disrupt the operation of CSs [43]. Tap water contains large amounts of calcium, which are deposited on the walls of coolers, while distilled water causes rapid corrosion of the walls. The best water for radiators is water treated with inhibitors (anti-corrosion agents) [105].

An empty CS cannot be refilled with 100% antifreeze, as the concentrated antifreeze can freeze at –12.2°C rather than the –37.2°C reached with a 50/50 mix.

Coolants are colored to facilitate the identification of the coolant in an engine. The lack of its brilliant color indicates that a coolant starts finishing its service life [43].

There are some colour groups for coolants applied in combustion engines [43] (Table 1) including:

1. IAT (Inorganic Acid Technology) – Bright Green

These coolant blends were utilized by automobile manufacturers through 1994, and by Ford continuing through 2002. Asian and European car manufacturers have withdrawn it from use since 1990. IATs contain phosphates and silicates and mate properly with cast iron engine blocks and Cu or Al radiators. They should be reconditioned every 2 years or 36,000 miles. If it remained in an engine above these restrictions, the unavoidable creation of clogging solids can weaken a CS's performance. Heater core obliterations occurred under the irregular coolant replacement [43].

IATs contain silicates and nitrates, which form a protective barrier over the entire surface of the CS from the inside. Such fluids quickly lose their properties, and if not replaced for a long time, they form deposits and sediments blocking water channels. They are predestined for ICEs with a cast iron block and an aluminum head, as long as they are replaced at least every two years [105]. IATs comprise inhibitors in the form of silicates [159]. IATs are rarely used as factory fill-in ICEs due to the fast depletion rate of their additives enhancing the needed frequency of changing for such coolants, usually every two years or 24,000 miles [1].

2. OAT (Organic Acid Technology) – Orange, Red, Blue, or Dark Green

Such coolants comprised no phosphates or silicates were applied in many cars produced after 1994. A benefit of these coolants was an prolonged coolant life until 5 years or 150,000 miles [43]. OATs comprise inhibitors in the form of organic acids and are applied in engines of GM, Saab, and VW vehicles [159]. OATs are typically changed every five years or 50,000 miles [1]. They form a much thinner protective layer than IAT coolants, no less effective. Thanks to this, they receive and give off heat more easily than IAT. OAT fluids are used in engines where there are no lead solders in the coolers, as organic acids very negatively affect such connections, causing their destruction, which results in leaks [105].

FleetGuard [59] point out that all Organic Acid Technology (OAT) or Extended Life Coolants (ELC) products are easier to maintain and more tolerant of contamination (brazing flux, hard water, etc.) than older technology products. However, liner pitting performance and elastomer compatibility varies on the types and quantity of organic additives used. 2-ethylhexanoate (2-EH) commonly used organic additive in both light and heavy-duty applications, have a negative impact on silicone elastomers, including head gaskets, rocker cover housing gaskets and silicone hoses. 2-EH induces degradation of the silicone elastomers over time, with the gasket and hose material shrinking and becoming brittle. The failed silicone head gaskets allow exhaust gas to bypass the gasket, leading to acidification of the coolant and enhanced corrosion. Silicone head gaskets are most common in high-horsepower applications, but silicone hoses are common in various less-power automobiles.

According to Cummins Engineering Standard 14603 (CES14603), coolants should be compatible with silicone elastomers. All Fleetguard coolants are 2-EH-free and meet the requirements of CES14603 [59].

Nitrite-free OAT products are less effective at protecting liners from pitting than nitrite-containing coolants. However, the formulation of the nitrite-free Fleetguard ES Compleat OAT provided maintaining liner protection close to that of a nitrite-containing coolant. The ES Compleat OAT is Nitrite, Amine, Phosphate and Silicate Free and provides an effective 1000000 millages of the engine. It provides antifreeze and anti-boil protection, very good liner pitting and corrosion protection, and is superior for contact with aluminum and solders [60].

3. Si-OAT (Silicated HOAT) – Purple

They contain inhibitors in the form of Silicates and Organic Acids and are applied in engines of Mercedes-Benz, Audi, VW, Porsche and other vehicles [159].

4. HOAT (Hybrid Organic Acid Technology) – Yellow, Turquoise, Pink, Blue, or Purple.

These coolant blends liebetween the IAT and OAT types and are often applied in newer Chrysler products besides in European and Asian automobiles [43]. HOATs contain organic additives and silicate agents to replace IAT fluids for better corrosion protection and longer drain intervals [105]. HOATs comprise inhibitors in the form of organic acids and silicates and are applied in the engines of Ford, Chrysler and European vehicles [159]. Such coolants are typically changed every five years or 50,000 miles, although in some cases intervals as long as ten years or 150,000 miles are also met [1].

5. HOAT (Hybrid OAT, Phosphate-free) – Turquoise

They contain NAP Free inhibitors and are applied in engines of BMW, Volvo, Tesla, Mini, and others [159].

6. P-HOAT (Phosphated HOAT) – Pink or Blue

They contain inhibitors in the form of Phosphates & Organic Acids and are applied in the engines of Toyota, Nissan, Honda, Hyundai, KIA & other Asian vehicles [159].

7. Dex-Cool – Orange

Being of an OAT type, they were introduced in 1995 for GM cars. When drivers faultily inserted green coolant into systems comprising the Dex-Cool system, obliterations often appeared. However, Dex-Cool is a plausible coolant but cannot be blended with other antifreeze [43].

Although some producers offer a so-called 'universal' 150,000-mile prolonged life coolant (yellow in color) [158, 159], introducing this to the ECS is risky. When any antifreeze is required, it is better to use the type predestined for a given engine [43]. Dex-Cools should be replaced every 3-5 years [35].

Table 1. Properties and marks for various coolant

Type	Inhibitor	Vehicles	Color	Periods between coolant change	Refs
IAT (Inorganic Acid Technology)	Silicates	Older Vehicles	Green	2 yrs/24,000 miles	[130, 159]
OAT (Organic Acid Technology)	Organic Acids	GM, Saab, VW, Opel	Orange	5 yrs/50,000 miles	[130, 159]
HOAT (Hybrid OAT)	Silicates & Organic Acids	Ford, Chrysler, European	Yellow	5 yrs/50,000 miles	[130, 159]
HOAT (Hybrid OAT, Phosphate-free)	NAP Free	BMW, Volvo, Tesla, Mini, Audi, Jaguar, Mercedes, Porsche, Rolls-Royce, Saab, VW	Turquoise		[130, 159]
P-HOAT (Phosphated HOAT)	Phosphates & Organic Acids	Toyota, Nissan, Honda, Hyundai, KIA & other Asian vehicles	Pink/ Blue		[130, 159]
Si-OAT (Silicated HOAT)	Silicates & Organic Acids	Mercedes-Benz, Audi, VW, Porsche, Bentley, Lamborghini	Purple	5 yrs/150,000 miles (LAppl) 3 yrs/300,000 miles (HAppl)	[130, 159]

According to [130], engines made in Asia have had issues with poor HT. Therefore, their coolants, instead silicates, utilize phosphates and carboxylates as the anti-corrosive additive. Engines made in Europe utilized silicates and carboxylates instead of phosphates, as hard water, comprising calcium and magnesium, reacts with phosphate inhibitors in EC, inducing the scale to settle on engine inner surfaces.

Some physical properties of various coolants are presented in Table 2 [19, 95, 154].

Hyper Lube [130] proposed three coolant additives:

1. Hyper Cool Radiator Cleaner and Super Flush formula consistent with all petrol and diesel engines. The coolant can purge and secure the engine within 30 minutes. Such a heavy-duty formula can contact all CS elements, including plastic and Al ones. It effectively removes rust, scale, residue and solder bloom. This formula also comprises water pump lubricant and corrosion inhibitors, promoting keeping the cleaner engine running.
2. Hyper Lube's Diesel Super Coolant, a supplemental coolant additive (SCA) is compatible with any standard diesel EC. It is predestined to secure present, turbocharged and intercooled diesel engines. It enhances HT and lowers engine part temperature by up to 9°C. A 50/50 blend of glycol and water lower an ET to 197.8°C, while that mix with super coolant added decreased it to 192.8°C. Just water lowers an ET to 194.4°C, while a blend of water and supper coolant decreases it to 181.1°C. This coolant improves the effectiveness of regular coolant, enhances fuel economy by up to 2%, boosts power and acceleration and secures against corrosion.
3. Hyper Cool Super Coolant, an EC system additive compatible with nearly every type of EC. It can lower ETs

by up to 25°C. A 50/50 blend of antifreeze and water lowers an ET to 110°C, while a 50/50 mid and super coolant decreases it to 105.6°C. Water only decreases an ET to 103.9°C, while a mix of water and super coolant lower in a decreased temperature of 90°C. Hyper Cool Super Coolant enhances engine power and ameliorates engine warm-up in chill environments.

According to [153], present water-based engine coolants (WBEC) are obtained by introducing corrosion inhibitors (CI) and anti-freezing agents (AFA) to water first deionized to eliminate corrosion factors (CF). They compared properties including CI, CF and AFA of water-extract from fermented ground maize (WEFGM) to water as the base fluid (BF) for the production of WBEC. The CF found in two WEFMG samples, exhibited pH values of 2.82 and 2.67, conductivity of 1941 and 1786 µs/cm, Pb of 0.06 and 0.05 mg/L, and Zn of 0.74 and 0.89 mg/L, respectively. CI existed were 12.25 and 22.51 mg/L of phosphates and 5 and 6 mg/L of nitrates, while AFA appeared were 5.29 and 2.38 mg/L of EGs and 4.74 and 2.15 mg/L of PGs from the 2 samples, respectively. The WEFGM was a cheaper BF for WBEC than water due to the occurrence of CI and AFA in the former.

In case of unexpected traffic issues, one can add distilled water to the CS. However, this is a temporary fix, and the system leak must be inspected, and the coolant blend either amended to rebuild preservation or the system rinsed and replenished. A new coolant can be added to the old one only when the former is of the identical type and color as the present antifreeze in an ECS. Non-adhering to this principle can induce the failure of the engine [43].

The most sensitive to improper mixing of coolants are inhibitors, which, depending on the type, are effective only at a certain pH. Mixing unsuitable fluids and changing the pH environment not only deteriorates corrosion protection but also allows the formation of an aggressive substance [105].

Introducing inappropriate antifreeze to the ECS can lead to coagulation of the coolant and clogging the radiator or the whole system. If badly clogged, the system cannot be readily rinsed and may require an expensive full de-installation for decontamination [43].

According to [35] a coolant needs to be changed when:

- the coolant light coming on points out reduced coolant levels as well as the engine operating too hot. This can be caused by a coolant leak
- temperature on the gauge is higher than normal. If the needle moves upward or downward, a CS is compromised
- the tell-tale puddles of colored toxic fluid appear below the vehicle
- sweet smell near the car can also point out coolant leakage
- the heater fails due to a leak of enough coolant amount
- coolants tested periodically with chemical strips exhibited acidic pH levels.

The coolant levels need to be checked every time refueling or at least once every two weeks. At least this level should be checked once every 6 months, i.e., before both summer and winter. If the level is under the max line, this can result from natural and gradual loss and the need to top up the reservoir with the manufacturer's recommended coolant. However, if the level falls under the minimum mark, one needs to refill the reservoir and inspect for a few days if the level dips under the max line every time to the point of the necessity to refill every time. This may point out a leak in the system.

EG antifreeze is highly poisonous when exposed via fumes, skin contact, and ingestion.

Coolants aggregate heavy metal contamination during circulation through the engine. It is necessary to apart store contaminated and uncontaminated antifreeze. Recycling coolant contaminated by gas or engine oil is impossible at regular recycling facilities. Uncontaminated antifreeze should be recycled, but contaminated ones should be directed to a hazardous chemical disposal facility.

Summarizing this part, it can be noticed that the unsuitable freezing temperature of the coolant can cause its freezing under low temperatures leading to damage to the radiator or engine block. The unsuitable boiling temperature of the coolant can provide the sudden growth of air/steam pressure in the CS resulting in the destruction of its components or their arrangement.

Table 2. Physical properties of coolants

Coolant	k	c	ν				ρ	T_B	T_{FP}
			T_1	T_2	T_3	T_4			
W	2.21	4181	-	1.79	0.68	0.28	1000	100	0
50/50 W/EG	1.3	3284	19.34	8.48	2.39	0.71	1082	107.8	-37.8
40/60 W/EG	1.45	3473	13.76	6.09	1.87	0.61	1073	105.5	-23.9
60/40 W/EG	1,17	3088	30.08	12.68	3.03	0.78	1102	110	-47.8
50/50 W/PG	1.22	3535	61.82	19.52	3.34	0.81	1061	105.5	-33.3
40/60 W/PG	1.39	3707	40.92	13.12	2.4	0.66	1054	103.8	-21.1
60/40 W/PG	1.06	3343	114.9	33.68	4.62	0.94	1068	107.2	-50.6

(k [W/m^{2}K] – TC at the temperature of 98.9°C, c [J/kg K] – specific heat at the temperature of 21.1°C, ν [cP] – kinematic viscosity at temperature: T_1 = –17.8°C, T_2 = –1.1°C (0°C for W), T_3 = 37.8°C, T_4 = 98.9°C, ρ [kg/m^3] – density at the temperature of –1.1°C (0°C for W), T_B [°C] – boiling point, T_{FP} [°C] – freezing point)

W/EG – Water/Ethylene Glycol blend, W/PG – Water/Propylene Glycol blend

The admissible crossing period of coolant exploitation causes paraffin releases and a fall in heater patency. Insufficient level of coolant in a CS reduces its efficiency and leads to the engine overheating.

4.3. Nanocoolants

A very innovative direction in the development of CSs is the application of nanoparticles (NPs) to coolants.

Ibrahim et al. [86] noted that ICE radiators use forced convection during the HT process under coolant circulation. In addition to water, glycerol, and EG, also various nanofluids (NFs), and nanocellulose are used in such radiators.

According to Naraki et al. [115], using a car radiator with NC under laminar flow provided the overall HT coefficient much more than that of the BF.

According to [15], enhanced thermal efficiency of the NCs resulted from many mechanisms including TC intensification, gravity, inter-phase frictional force, sedimentation, dispersion, ballistic phonon advection, non-uniform shear rate, nanoparticle migration induced by viscosity gradient and layering at the solid-liquid interface. The hydrothermal characteristics of NFs are sensitive toward particle size and shape, material and percentage strength, BF features and pH value, fluid temperature and additives.

NCs belong to the class of NFs, taking the form of base liquids with dispersed NPs of size less than 100 nm [104]. As a base liquid, the most often used water (W), EG and their mixtures in various proportions. NPs having a high TC, when suspended in conventional liquids, improve the TC and HT efficiency of such liquids. This enhances the HT rates while also changing the property of the resulting fluids allowing them to be the next generation of HT fluids called nanocoolants (NCs) [112].

Many studies were conducted regarding the enhancement of the convective HT performance using NPs [80], [137]. However, the application of NFs, due to their enhanced heat-carrying capacity, needs a decrease in the pumping power required despite increased resistance to flow compared to fluids without NPs.

Among the most widely presented and studied NPs in the composition of NFs in the scientific literature, the following types can be distinguished:

Metals: Cu, Ag, Au, etc. The particle size is ranged from 10 to 110 nm. For example, Gopa et al. [66] reported the overall effectiveness of the radiator improvement by 14% with a 0.01% volume fraction Cu NPs-based coolant (size of Cu NPs about 57 nm).

Oxides: Al_2O_3, CuO, ZnO, MgO, SiO_2, ferrofluid and magnetized ferrofluids (containing Fe oxides at various levels of oxidation). This NP type has been studied both theoretically and experimentally. The peak of scientific interest in the application of this NP type as a component of NF for engine cooling approximately began between 2010 and 2019.

Carbon: Diamond, SWCNT, MWCNT, Graphene. The history of application and research of this NP type in ICEs began almost simultaneously with the discovery of the corresponding particles. At the initial stage, the use of particles of this type was largely represented in studies regarding the cooling and lubrication of an internal combustion engine with engine oil with the addition of carbon particles of various types. As some types of carbon NPs (for example, graphene) have very high TC (up to 1000 W/mK [129]) their use as an additive to NF coolant is logical.

In addition to NPs and BFs, a NF can contain various surfactants. For example: Anionic like Sodium Dodecyl Sulphate (SDS), Cationic like Cetyl Trimethyl Ammonium Bromide (CTAB), Non-ionic like Gum Arabic GA, Triton X-100, Amphoteric like lecithin, hydroxylamine, etc. [29].

Summary of the TC, theoretical and experimental investigations for NFs as a coolant for automotive engine radiators were comprehensively performed by Karaar Mahdi Al-Araji et al. [6]. It seems rational to build the literature analysis of NFs in this paper in a similar way where investigations are mainly divided into theoretical (mathematical, numerical modeling and simulation) and experimental studies, but giving more recent references and adding information about emerging trends in this field.

Considering early theoretical studies one should mention the following publications: [156] (Al_2O_3, CuO/W-EG), [31] (CuO/W), [81] (CuO/EG), [134] (Al_2O_3/W), [70] (TiO_2, Fe_2O_3, CuO/W), [2] (Al_2O_3, Au, CuO, TiO_2/W), from which one can draw the following general conclusions that use of Al_2O_3 NPs enables greater extent HT coefficient comparing to TiO_2, Au, CuO, and Fe_2O_3. NPs impact on laminar to turbulent flow transition and allow to enhance Brownian motion. Further theoretical studies were performed by [51] (Al_2O_3, CuO/W), [56] (Al_2O_3, CuO/W), [82] (MWCNT–Fe_3O_4/W), [85] (Al_2O_3/W), [74] (Al_2O_3/W, EG), [17] (Al_2O_3/W, EG), [63] (MgO, ZnO/W, EG), [83] (TiO_2/W), [52] (Al_2O_3, CuO/W), [90] (Al_2O_3, TiO_2, ZnO, SiO_2/W), [99] (SiO_2/W), [114] (Cu/EG), [140] (Al_2O_3/EG), [141] (TiO_2/EG-W (1:3)), [119] (Al_2O_3/W), [10] (Al_2O_3, CuO/EG). Summarizing those studies one can notice that the efficiency of the HT process is linearly related to the fraction of NPs in the range of volume concentrations from 1 to 6% (depending on the NP type), which gives an increase of HT coefficient by e.g. 17.1% at 3% concentration of ZnO and MgO NFs, 10% for CuO/W NF at 2%, 12.03% and 14.31% at 4% concentration of Al2O3/W comparing to a BF for given conditions. The friction coefficient and PD rise with utilizing NFs considerably. For instance, at Re of 1750 and NP amount of 0.07, they rose by 271 and 267% for Al2O3/W and 266 and 226% for CuO/W, respectively [52].

The authors of Refs: [4] (TiO_2/W), [7] (MWCNT, CuO, Al2O3), [24] (Al_2O_3/W), [69] (ZnO/W), [84] (SiO_2), [93] (Fe-magnetised NPs), [98] (SiC-MWCNTs), [99] (SiO_2/W), [118] (CaC2/W), [124] (Fe_2O_3, CuO/W), [126] (CuO, Al_2O_3/W, EG), [140] (Al_2O_3/EG), [144] (Al_2O_3/W, EG), [146] (MWCNT), [148] (Al_2O_3/W, EG), performed experimental studies on the impact of NFs on car radiator performance. Summarizing and generalizing the research outcomes one can notice that:

- major share in HT increase is flow rate for NF and volume fraction of NPs. The increase in HT due to the inlet temperature of the coolant is insignificant. Considerable increase in TC and specific heat of the fluid leads to an increase of Nusselt number.
- for many NF types, the concentration level of 0.5–1.0% (volume) brings positive effect. For instance: NC with 0.5% ZnO yields the biggest overall HT coefficient than

other NFs or the BFs [69]; on the other hand: the maximum values of friction factor enhanced to 22% for SiO_2 NPs dispersed in water with 2.5% volume concentration. The biggest Nusselt number rise up to 40% obtained for SiO_2 NPs in water. The Nusselt number of 1% SiO_2 NF at 80°C has 52% deviation than pure water but 32% at 60^{o}C [84]. Thus, an increase in the volume fraction above 1%vol highly rises friction leading to higher energy consumption of the pump. The more NP concentration the higher chance that the suspended particles fall into the sediment.

– use of NF allows designing compact-size radiators which also reduces the weight of the system.

Jadeja et al. [88] represented a profound review study for NF as a coolant in internal combustion engines. The authors noticed that among the various NFs the use of NCs with MWCNTs, Al_2O_3 and CuO can augment heat transport rate taking into account the balance between operating costs and efficiency. Also, they pay attention to the existing two NFs fabrication methods: (i) one-step technique and (ii) two-step technique. The two-step one is prevalent for oxide NPs. It is less valuable with metallic particles than the single-step one. They emphasized the need for the proper identification of surface functionality, crystal structure, crystalline character, and stability of NPs inside the BF.

Considering the latest trends and challenges HT application using hybrid nanofluids (HNFs) one should notice the recent 2023 study Kumar et al. [94], where the authors have come to the following remarks from the extensive review:

1) The classical models applied to assess the rheological and HT efficiency of mono NFs cannot rate the HNF features precisely. Particularly, these deviations are more at higher percentage strengths.
2) Flow properties of HNFs are improved by the addition of hybrid NPs (HNPs). The relative viscosity of the HNF rose because of the formation of nanoclusters in the BF. These nanoclusters induce rises in the hydraulic diameters of HNPs enhancing the relative viscosity with the risen temperature, inter particles' cohesive force was weakened and subsequently the viscosity was reduced.
3) TC of HNFs is significantly more than BF and mono NFs of individual constituents. In the HNFs, metallic NPs form a new nanolayer on the metal oxide particle surface and create the thermal interfaces between grain boundaries of HNPs and BF, so that TC rise is considerably higher. As the temperature of NF increases the particles move at a faster rate, which intensifies Brownian motion and rises the TC.
4) HT characteristics of mono NFs are ameliorated by the addition of NPs as result of their refined thermosphysical properties and this amelioration is more for the HNFs.
5) Friction factor and PD are relatively more for the HNFs than for mono NFs and BF. The inclusion of HNPs develops more wall shear enhancing with volume fraction.

Interestingly, Ettefagi et al. [55] studied ECs comprising biodegradable carbon quantum dots (CQDs) in concentrations varying from 100 to 1000 ppm. For 200-ppm CQDs concentration, the coefficients of TC (k) and of convection HT (h) were improved by 5.7% and 16.2% compared to these of the BF, respectively.

In conclusion, it should be noted that the only increase in the efficiency of cooling processes in an ICE is not capable of leading to a significant energy effect for the propulsion system as a whole. First of all, this is due to the fact that even the best results of NFs, which give good increases in the HT coefficient, cannot compete with cooling methods based on the phase transition of the coolant (where huge values of HT coefficients are achieved during evaporation or condensation). Therefore, it seems extreme perspective combines the positive effects of NF with phase transition cooling schemes, where the removed heat is recuperated for increasing engine performance. The stability of NPs in ECs plays a very important role.

5. Pressure device for coolant change

A new device [169] for the coolant changes in vehicles up to 3500 kg was developed after some observations.

The classic method of coolant change comprising the hose's disassembly from the radiator, unscrewing the plug from the engine block, and down the fluid cannot assure 100% removal of coolant.

The ITALCOM device [87], shown in Fig. 2, allows the removal of used coolant, rinsing the CS, and filling it with fresh coolant using the hypotensive method. Before the realization of coolant change with such a device, the equalizing tank of the CS is open to lower in-system pressure, and then the used coolant flows away to tank 4. The EM 1 and monometer 7 steering operation of the pomp 2 is connected to the vehicle battery by switch 8. When the pressure in the CS falls below 400 hPa, what follows after the unlocking of the CS thermostat, it causes starting of engine 1 driving pump 2. The latter presses fresh coolant to the radiator of the system. The fresh coolant is pressed into the CS cyclically, which is realized by locking and unlocking the thermostat. In one cycle, about 1,5 liter of fresh coolant is pumped into the CS. When the pressure in the CS grows up to 600 hPa, what follows after the thermostat lock, relay 6 causes the separation of engine 1 from the battery and disconnection of coolant pump 2. The use of under-pressure can cause clamps of pipes during coolant change, which causes a pause in flow.

The new device [169] to change the coolant in the CS (Fig. 3 and 4) also contains tank 3 with fresh coolant connected by a pipe with electric pomp 2 connected via a pipe to the vehicle radiator, similar to the scheme in Fig. 2. The pump 2 is connected with the EM 1 possessing pins to link to the outer power supply. The pump 2 is connected simultaneously by the relay with the manometer possessing pins to link to the external power source supply (e.g., vehicle battery), but the EM and manometer are separately connected with the external power source. The pump 2 is connected via a rubber pipe and its connector to the vehicle radiator. The EM 1 is connected simultaneously by relay 6 with manometer 7 possessing pins to connect to the vehicle battery. The EM 1 and monometer 7 are connected to the battery by switch 8. The device also contains tank 4 for waste coolant connected via a rubber pipe and its connector to the vehicle thermostat. The new device allows the coolant change by the pressure method, eliminating the pipe clamping during the coolant change process.

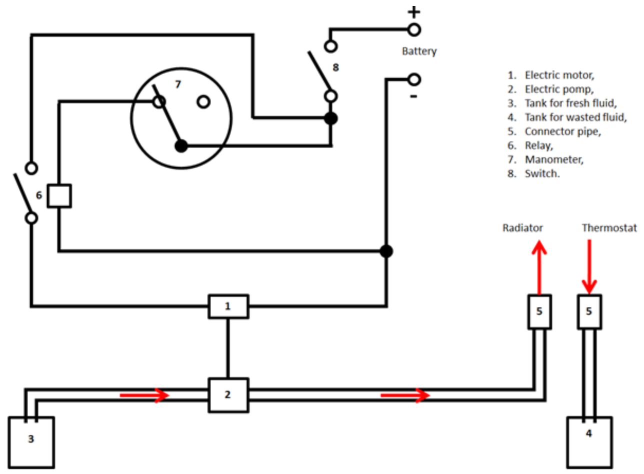

Fig. 2. The scheme of device for cooling fluid change

Fig. 3. The device for coolant changes and the control pressure gauge with start switch

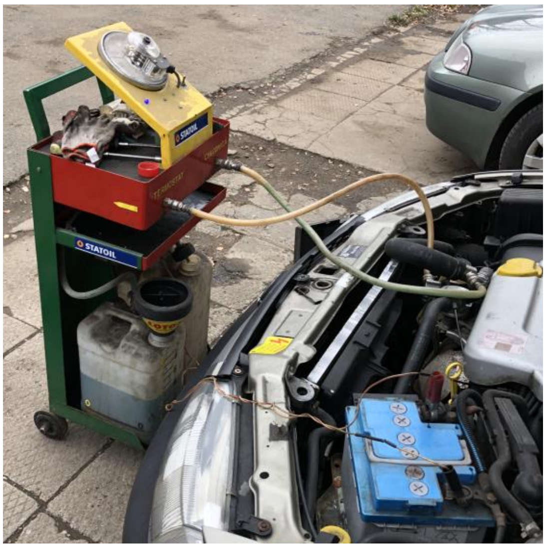

Fig. 4. The device for coolant connected to the vehicle.

Summary

Various CSs are developed in classical ICE vehicles and hybrid and electrical ones. Various systems for cooling HV BPs in HEV and EVs using various coolants and TM approaches are under development. The existence of various coolants used for ICEs and HV BPs can hinder the identification of leak sources, especially in HEVs.

The use of NCs in CSs may be hampered by the tendency of NPs to agglomerate, favoring the local accumulation of deposits in the flow channels, which may even lead to their clogging. The effect of the addition of oleic acid, which is one of the stabilizers preventing NPs agglomeration [170] is not well recognized in the case of NCs. In addition, the influence of adding NPs to base coolants on changing their toxicity is unknown. Therefore, further research is needed on these issues.

Various devices facilitating coolant changes and differing complexity and costs are under development.

Nomenclature

AC	air cooling
ACS	air conditioning system
BC	battery cooling
BF	base fluid
BP	battery pack
BTM	battery thermal management
BEC	branded engine coolant
BEV	battery electric vehicle
CF	corrosion factor
CI	compression ignition; corrosion inhibitor
COP	coefficient of performance
CQD	carbon quantum dot
CS	cooling system
CT	coolant temperature
CTS	coolant temperature sensor
DTC	diagnostic trouble codes
EC	engine coolant
ECS	engine cooling system
ECU	electronic control unit
EG	ethylene glycol
EGR	exhaust gas recirculation
EM	electric motor
ET	engine temperature
EV	electric vehicle
FCEV	fuel cell electric vehicle
HEV	hybrid electric vehicles
HNF	hybrid nanofluid
HOAT	hybrid organic acid technology
HNP	hybrid nanoparticle
HT	heat transfer
HTCS	high-temperature cooling system
HV	high voltage
HVAC	heating, ventilation, air conditioning
HX	heat exchange
IAT	inorganic acid technology
ICE	internal combustion engine
LIB	lithium-ion battery
LC	liquid cooling

NC	nanocoolant
NF	nanofluid
NP	nanoparticle
OAT	organic acid technology
PC	phase change
PCM	phase change material
PD	pressure drop
PG	propylene glycol
PHEV	plug-in hybrid electric vehicle
TC	thermal conductivity
TM	thermal management
TP	thermal performance
W	water
WBEC	water-based engine coolant
WEFGM	water-extract from fermented ground maize

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