

The influence of the drive type in city bus on the cooling system parameters

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Abstract. The study discusses the influence of the type of drive used in city buses on the elements and parameters of the cooling system operation. Currently, commonly used are the combustion engines powered by diesel fuel and, to a lesser extent, combustion engines powered by natural gas. However, due to air pollution in cities, measures are taken to reduce vehicle emissions. Consequently, city hybrid or electric buses are developed. In all systems there are losses generating heat, which has to be removed. However, the amount of heat varies depending on the type of drive system and, more importantly, also greatly varied is the permissible operating temperature of the drive components, what results in the need to use different solutions of cooling systems. The study is an analysis of cooling system operation parameters for individual drive solutions and the solutions necessary to meet these parameters are presented.

1. Introduction

In cities and urban agglomerations, public transport is based on a bus, tram, rail or metro system. The mobility of passengers, defined by the number of passenger kilometres during the year, is estimated at approximately 12,000 km per person per year in the EU, while in Poland it is estimated at approximately 8,800 km per person per year [3]. Bus transport has the largest share in mass transport of people. In the EU, buses account for approximately 11% of all heavy-duty vehicles used [4]. The number of city buses carrying passengers in Polish cities is approximately 12,000 [3,5]. Most of the bus fleet is equipped with a drive based on diesel-fuelled compression-ignition engines. Alternative fuel, in the form of natural gas or LPG, is becoming more and more popular. In addition, in response to the transport decarbonisation project, hybrid or electric solutions are being developed, including the use of hydrogen fuel cells. The lack of exhaust emissions and, consequently, pollution in the place of the vehicle's use does not mean that there is no negative impact on the environment. The total impact of the vehicle on the natural environment should be determined by taking into account all the components, namely [4]:

- type of primary energy source
- type of carrier of the energy powering the vehicle
- type of drive source used
- production processes

For example, about 90% of electricity generated in Poland comes from the process of hard coal and lignite burning [6]. At the same time, the demand for energy of the electric bus is much smaller than the demand of the bus with a conventional CI combustion engine or a hybrid system based on the combination of an combustion engine and electric motor (Figure 1).



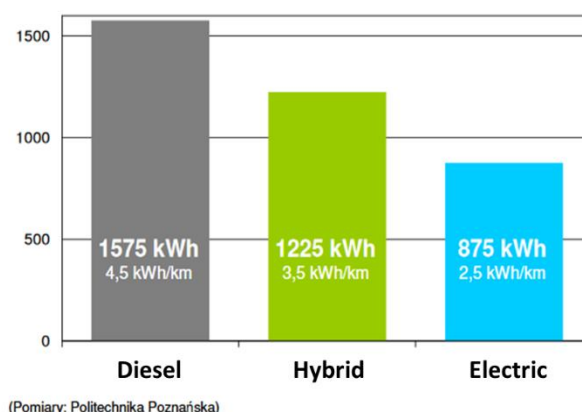


Figure 1. Comparison of energy consumption of buses with various types of propulsion in the SORT 2 test (12 m long bus with the total weight of 18 tons, daily cycle: 350 km/day) [7]

The use of each of the methods of vehicle propulsion mentioned above is associated with the generation of waste heat, which must be removed. At the same time, depending on the type of drive, the permissible operating temperature of the component parts varies considerably. As a result, a cooling system is required in all vehicles but the operating parameters, such as the temperature to which the coolant is to be cooled, the amount of rejected heat, or the mass flow of the coolant significantly diverge from each other in the individual drive system solutions.

2. Drive with an internal combustion engine powered by diesel fuel

Internal combustion engines have a long history of use in vehicles. Their design is being constantly refined, and for several years, the development of engines has been subordinated to the successively introduced standards limiting the emission of harmful substances in the exhaust gases. The need to meet the required emission limits forces a continuous improvement of the combustion process in order to reduce the formation of exhaust toxic components and the application of exhaust aftertreatment systems.

Cooling systems of modern heavy-duty engines (Figure 2), similarly to other engine systems, are becoming increasingly sophisticated, contain an increasing number of elements and, in order to optimize the engine operating parameters, the operation is continuously monitored by a variety of sensors. An increasing number of engine components requiring constant temperature (hence cooling) results in an increased heat rejection to the cooling system [15,16]. The temperature difference of the coolant obtained in the heat exchanger must be maintained at a constant level of approximately 6 – 8 K, because an excess temperature gradient may lead to the damage of engine components in contact with the coolant. Reception of excess heat is realized by increasing the coolant flow rate. The need to cool many engine components at the same time results in an extended coolant flow distance, hence greater major and minor head loss, directly affecting the pump load. Therefore, a greater heat exchange area of the radiator responsible for heat dispersion is necessary too. It is possible by increasing its size without changing the design or introducing design changes of the heat dispersing components aimed to improve the radiator's efficiency. Additionally, within the Euro 6 Emission Standards, for some of the engines the permissible difference between the charging air downstream of the intercooler and the ambient temperature has been reduced. This forces the application of a larger or more efficient intercooler. Nevertheless, in both cases a greater heat transfer is related to greater heating of the cooling air and since the intercooler is most often located in front of the coolant radiator the air cooling the heat exchanger has higher temperature and the heat exchange conditions are worse.

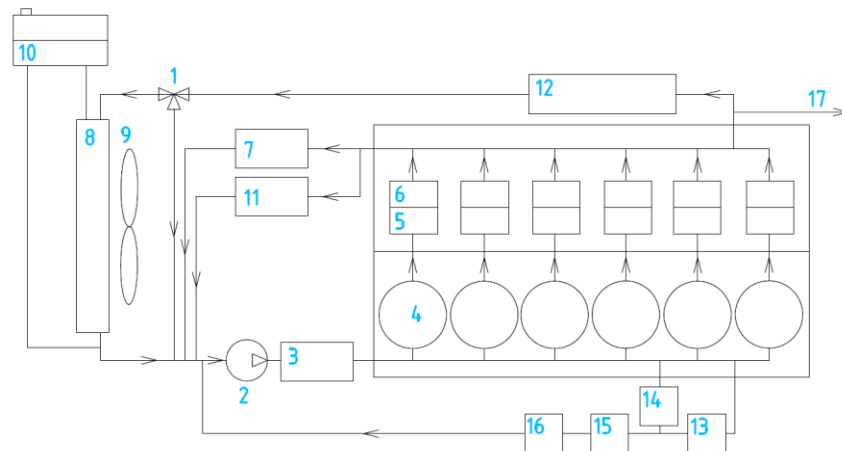


Figure 2. Diagram of a heavy-duty engine cooling system meeting the Euro 6 Emission Standards [16]

1 – coolant thermostat, 2 – coolant pump, 3 – oil – water heat exchanger, 4 – cylinder, 5 – lower coolant level in cylinder head, 6 – upper coolant level in cylinder head, 7 – heater heat exchanger, 8 – radiator, 9 – fan, 10 – coolant expansion tank, 11 – urea heater, 12 – exhaust gas recirculation cooler, 13 – air compressor, 14 – fuel cooler, 15 – exhaust gas recirculation positioned, 16 – transmission oil – water cooler (optional), 17 – retarder (optional)

In order to improve the efficiency of converting energy from the fuel, higher and higher temperatures of coolant are used (Figure 3) [15,17]. This practice aims at increasing the temperature of the engine work cycle by reducing the heat losses from the combustion chamber to the environment. To maintain higher and higher temperatures in the cooling system it is necessary to use higher and higher values of pressure. Given the European climate, cooling systems must meet the requirements for ambient temperature of 40°C - 45°C. This results in a large difference between the ambient temperature and the temperature of the coolant, which is beneficial as far as the heat exchange process is concerned.

The cooling module in vehicles with heavy-duty engines consists of a radiator, a charge air cooler, a condenser of air-conditioning system and a fan or fans. If the fan drive is hydraulic, the cooling module also includes the oil cooler of the fan drive system. In addition, the cooling module can include an air cooler of the pneumatic system.

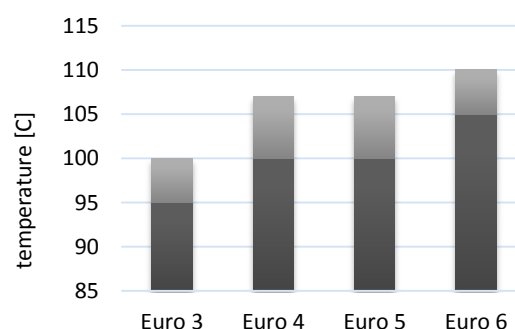


Figure 3. Values of coolant temperature depending on the Euro Emission Standards [15]

3. Drive with an internal combustion engine powered by natural gas

Natural gas is an alternative source of energy for combustion engines, exhibiting good calorific and emission-related parameters. Due to its low energy density (it has to be accumulated under high pressure) and a limited distribution network, natural gas is best for stationary engines or engines used in municipal service and public transit vehicles. Natural gas combustion process is characterized by a

lower flame propagation rate compared to other fuels, the consequence of which is the extension of the combustion towards the power stroke and a greater thermal load of the engine, which is why the adaptation of a diesel engine to natural gas fuelling requires an increased efficiency of the cooling system. For the engines, shown in Table 1, the amount of heat rejected to the cooling system is greater by approximately 13% for the natural gas fuelled engine at a simultaneous reduction of the maximum admissible coolant temperature by 10 K. The lower difference of temperature between coolant and cooling air influence the reduction of the specific heat rejection of heat exchanger, consequently an application of greater space of heat exchange is necessary. The extension of the combustion process increases the exhaust gas temperature at the moment of exhaust valve opening, which, in the case of turbocharged engines, may improve the turbocharging efficiency. The lower rate of flame propagation is associated with a lower rate of pressure increase in the combustion chamber during the combustion process. As a result, the engine powered by natural gas emits a noise of about 1-3 dB lower than the engine powered by petrol or diesel fuel [3,4].

Table 1. Selected engines data at the 25°C ambient temperature

		Diesel Engine	Natural Gas Engine
Heat Rejection to Coolant	kW	152	172
Coolant Temperature	°C	105	95
Charge Air Temperature after Turbocharger	°C	175	180
Charge Air Temperature before Engine	°C	41	37
Exhaust Gas Temperature	°C	420	540

The use of natural gas to power city bus engines is beneficial due to the very low emission of particulate matter and nitrogen oxides in the exhaust gases (Figure 4) [5].

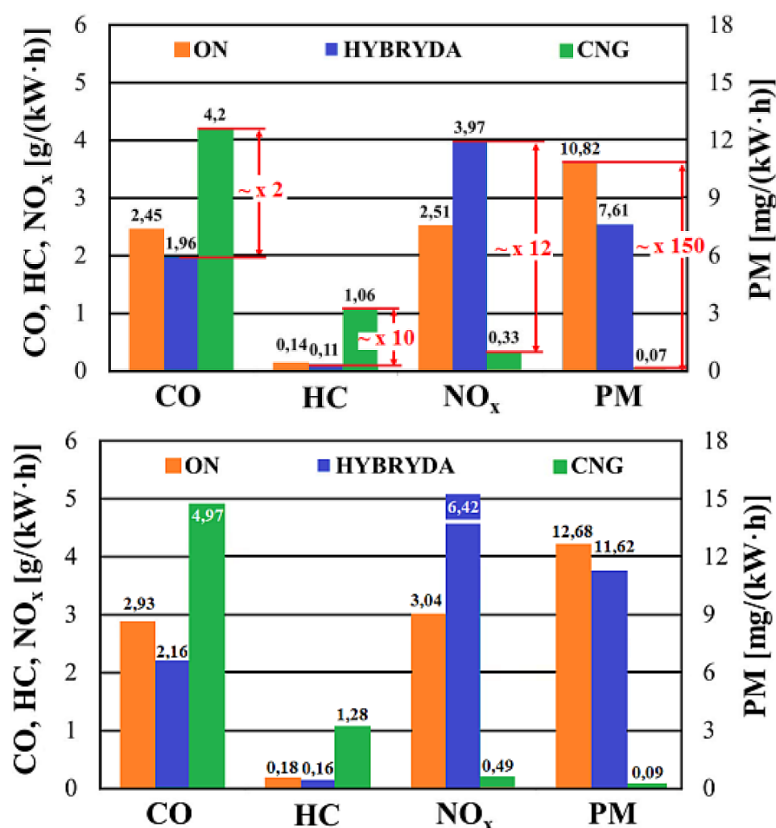


Figure 4. Unit emission of CO, HC, NO_x and PM determined in the SORT 2 test (top) and in the test on the city line (bottom) for buses with a compression ignition engine, a series hybrid system and a natural gas engine (ON – diesel fuel, HYBRYDA – hybrid, CNG – natural gas) [5]

Figure 5 presents the calculation model of the cooling module, and Table 2 includes the sizes of the basic components of the cooling module, calculated temperature values, the matching fan speeds and the resulting fan power demand.

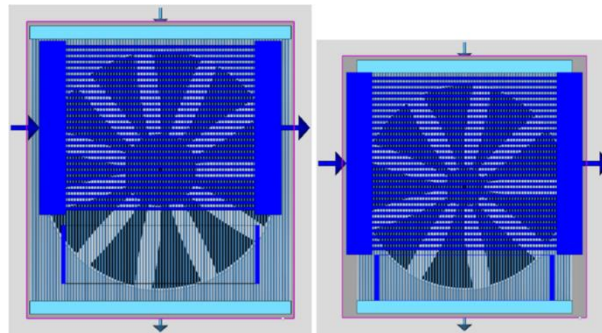


Figure 5. Calculation models of cooling modules with fans – left for the NG engine, right for the CI engine

Table 2. Calculation results for cooling modules (ambient temperature 45°C)

		CI Engine	Natural Gas Engine
Radiator Core	mm	800 x 750	900 x 900
Coolant Temperature after Engine	°C	103,3	93,5
Charge Air Cooler Core	mm	650 x 640	650 x 600
Charge Air Temperature before Engine	°C	58,3	53,5
Fan Diameter	mm	702/ 9 blades	814/ 11 blades
Fan Speed	rpm	2300	2000
Cooling Air Flow	kg/s	4,95	6,56
Fan power consumption	kW	21,3	28,6

A replacement of a diesel engine with a natural gas fuelled engine of the same operating parameters results in an increased amount of heat rejected to the coolant and a lower heat from the charging system to the charge air cooler, which is a result of lower charge air mass flow to the engine. Consequently, a selection of heat exchangers of different size is necessary, which requires more space for the fitting of the cooling module. A greater heat rejection (13%) of the natural gas fuelled engine to the cooling system compared to the diesel engine results in a larger frontal area of the radiator core by approximately 35%. The fan drive power demand also increases by approximately 34%.

4. Drive with a hybrid system

The method of operation of a city bus causes frequent starts and stops of the vehicle, which in a conventional drive generates significant losses. The hybrid drive combines two different sources of energy, usually an internal combustion engine with an electric motor. This allows to use the advantages and avoid the limits of each of the energy sources, but it also increases the costs of producing and purchasing a vehicle in comparison to the one with conventional drive [1,12]. The internal combustion engine can be powered by both conventional and alternative fuels, e.g. in the form of natural gas. The electric motor (or motors) uses energy stored in batteries or supercapacitors, and during braking, as a result of recuperation, up to 30% of energy is recovered [12,14]. The configuration of the hybrid system elements may be in series, parallel or mixed. The buses use the series and parallel systems (Figure 6). In both cases, fuel consumption is lower than in a conventional

bus and the difference may be 10%-20% on average [12,13,14]. At the same time, the choice of the internal combustion engine and electric motor combination affects also the level of fuel consumption, which directly translates into the emitted amount of carbon dioxide. The series system is the simplest hybrid drive solution. It is characterized by the lack of mechanical connection of the internal combustion engine with the drive wheels, thanks to which it can operate in the optimum range of rotational speed and load, obtaining good efficiency. As a result, a vehicle with the series hybrid system consumes less fuel than the one with a parallel system [14]. However, it can emit a larger amount of nitrogen oxides in the exhaust gases, even from a conventional solution, because the internal combustion engine is constantly loaded (Figure 4).

Combining the internal combustion engine with the electric system makes it necessary to expand the cooling system and, frequently, to also separate the arrangement of exchangers aimed at cooling the internal combustion engine and the electric system. This is caused by the significant differences in the required operating temperature. For an internal combustion engine, the optimum coolant temperature is 95°C - 105°C, while for electric components 60°C - 65°C. In addition, the electric system consists of many components to which the pipes delivering coolant must run and therefore an additional pump, which will have the right head lift and efficiency, should be chosen.

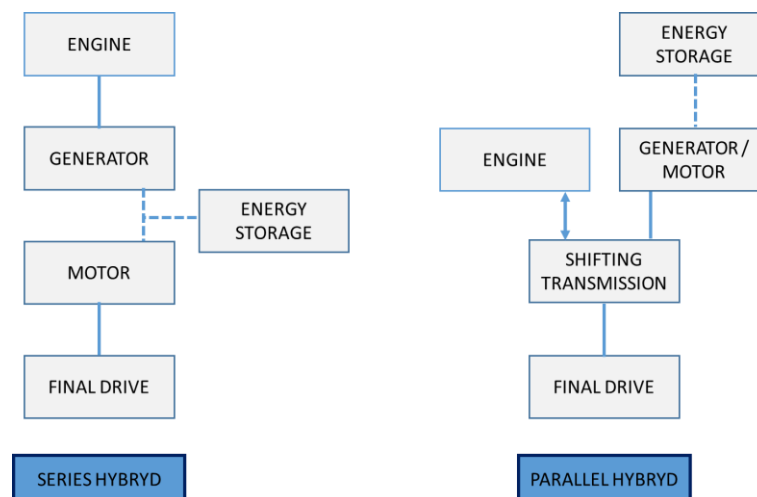


Figure 6. Configurations of hybrid systems – series and parallel [7]

5. Electric drive

The electric drive has an electric motor instead of an internal combustion engine and batteries or supercapacitors as an energy source instead of liquid or gas fuel. There is a difference between the batteries used in hybrid and electric vehicles, resulting from the specificity of the electric motor operation. Batteries used in hybrid systems should be characterized by high power density, while batteries used in electric drives have high energy density [1]. That is why Li-Ion batteries are used in electric vehicles. Batteries have large mass and size, significantly affecting the mass of the vehicle. At the same time, compared to fossil fuels, they are characterized by lower density of energy storage, what results in smaller range of the electric vehicle. In addition, the batteries deteriorate, their efficiency may decrease by about 5% per year [1], which also affects the systematic reduction of the range of the vehicle with electric drive. The time required to recharge the batteries is long, especially in relation to refuelling a vehicle with a conventional drive. The buses use plug-in charging systems with pantographic adaptation. Charging time is 4 - 5 h, and fast charging time is 2 h [12]. Li-Ion batteries generate significant amounts of heat during charging, which can damage them [8], especially at large capacities used in buses, therefore cooling is required. Also, the charging method affects the amount of heat generated. The efficiency of slow charging is at the level of 90%, while fast charging results in the reduction of the charging efficiency to about 60%, as part of the energy is used for

cooling [1]. Battery efficiency depends on operating conditions, including ambient temperature. In the negative ambient temperature, the capacity of the batteries decreases, resulting in a significant reduction in the vehicle's range. Electricity comes from a power plant, hence the impact of an electric vehicle on the environment depends on the fuels used in a given country for the production of electricity. Nevertheless, the use of electric drive eliminates exhaust gases emissions in the vehicle's place of use. An important advantage of the electric drive is the high efficiency and the availability of reaching maximum torque of the electric motor regardless of its rotational speed, which makes it very easy to start from a standstill, so frequent during the operation of the city bus. Similarly to the hybrid system, the braking energy is recovered by the electric motor, which works then as a generator.

The propulsion system of an electric vehicle consists of three main systems [1]:

- electric motor propulsion system – vehicle controller, power electric converter, electric motor and transmission
- battery system – batteries, Battery Management System (BMS) and charging unit
- auxiliary system – heating / cooling, electronic pumps and other electronic auxiliaries

Optimal working temperature of Li-Ion batteries is in the range from 15°C to 35°C. It ensures proper safety of use and the time of exploitation is extended. Vehicles are operated in different atmospheric conditions, therefore the ambient temperature may vary from negative values (e.g. -30°C) to positive values (e.g. +50°C), exceeding the optimum range for batteries. Therefore, a system that stabilizes the temperature of the batteries regardless of the environmental conditions is necessary. Such a system must consist of a heating element that operates when there is a negative ambient temperature as well as a passive and active cooling system, operating depending on the positive temperature range of the environment. The simplified diagram of the system is shown in Figure 7. A significant number of components of the system constitutes an additional mass, requires additional space in the vehicle and power supply, increasing the demand for power. In addition, the control system of the module is necessary.

In electrically powered buses, the most common solution is the use of two 400VAC traction motors, mounted in the rear axle of the vehicle, operating with two traction converters. In addition, there are a number of devices in the vehicle, such as coolant pumps, a power steering pump, an air conditioning compressor, and a pneumatic system compressor, all of which require a drive. Therefore, another converter and a series of inverters are necessary to control the auxiliary devices. Electric motors, converters and inverters require a constant operating temperature of 60°C - 65°C, therefore a cooling system is required. The amount of released heat is in the order of 30 - 70 kW, that is much lower than that of the combustion engine in a conventional drive, depending on the number of cooled elements. Smaller amount of heat to be transferred does not have to be equivalent with smaller size of the exchanger because much lower coolant temperature, if compared with the internal combustion engine, means less difference from the ambient temperature, which requires larger heat exchange surface. In addition, cooling of many elements located at different places in the vehicle is associated with an extensive system of pipes generating pressure drops in the cooling system.

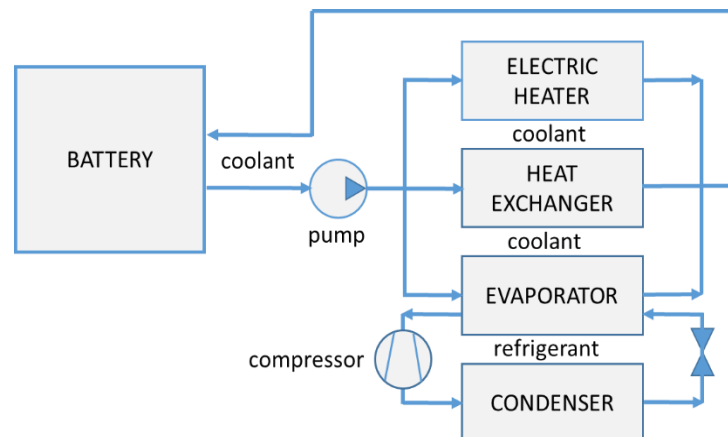


Figure 7. Diagram of the battery temperature stabilization system

6. Drive with fuel cells

Hydrogen is used in many industries, it is often obtained as waste gas of production processes. As a fuel, it has several times more energy density than conventional fuels, but due to its very low density, the energy value related to the volume unit is many times lower than it is for the other fuels [1,9]. Hydrogen can be combusted in the engine compartment, which achieves efficiency of 25% [1] or used to generate electricity in fuel cells. The efficiency of the drive with hydrogen fuel cells is on the order of 60% [1, 13]. Due to the low energy density of hydrogen, which makes storage difficult, the supply of the internal combustion engine with hydrogen is a solution for stationary engines operating with constant parameters in power generators [10]. Vehicles use fuel cells that generate electricity in chemical reactions of hydrogen and oxygen. There is no fuel combustion in them, therefore a much lower amount of heat and no exhaust gases are generated. In current solutions, hydrogen is stored in tanks under pressure of 35-70 MPa [1, 11, 13]. There are six main groups of fuel cells, some of which operate at a low temperature, on the order of 50°C - 200°C, and the rest at a high temperature, at the level of 650°C – 1000°C (Figure 8) [1]. In vehicles, PEM (proton exchange membrane) low-temperature cells are used [1,11,12,13]. The energy can be transferred directly to the electric motor that converts it to mechanical work, or stored in batteries or supercapacitors, but much smaller than those in an electric drive vehicle. The use of an electric motor for wheel drive enables energy recovery during braking. The obvious advantages of a vehicle with a fuel cells are the range and time of hydrogen refuelling, which are comparable to conventional drives [1,11,12]. The disadvantages are the cell production costs, several times higher than the internal combustion engine, as well as the costs of hydrogen storage. Hydrogen is a way to reduce carbon dioxide (CO₂) emissions from transport. However, fuel cells are not yet durable and further development works are necessary, therefore it is estimated that the technology of hydrogen drive is about 10 years behind electric vehicles [12].

The drive with hydrogen fuel cells consists of many of the same components as the electric drive system. Therefore, the cooling system for electric components is the same as in an electric bus. It is necessary to additionally cool the fuel cells, which, like batteries, require stable temperature conditions to work with optimal efficiency. The temperature of the coolant should be at 50°C and not higher than 65°C. If the ambient temperature is 0°C or below, heating the cell is required.

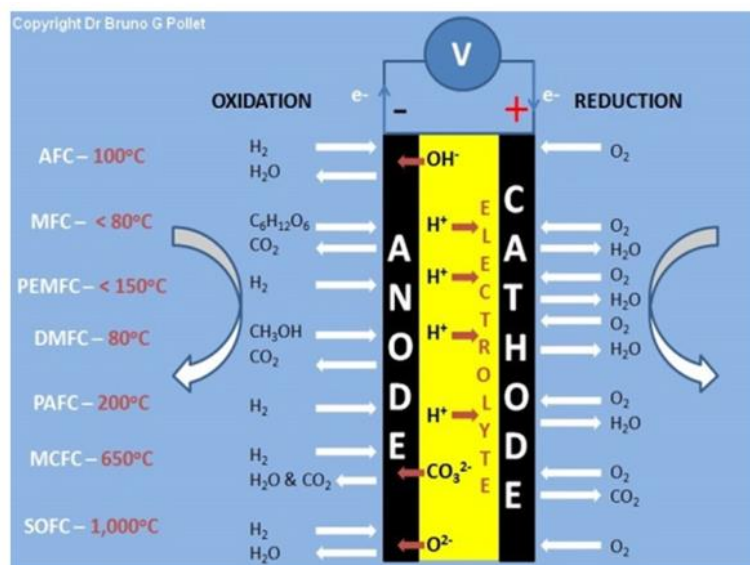


Figure 8. Types of fuel cells [1]

7. Summary

Regardless of the vehicle drive system used, a cooling system is always required. And although in the case of electric vehicles and those with hydrogen fuel cells the amount of heat released to the coolant is smaller than with the drives with internal combustion engines, the heat exchangers are not necessarily smaller. This is caused by the significantly lower coolant temperature values for electric components, which in combination with the ambient temperature of the vehicles in operation (40°C – 50°C in the summer period) is not favourable due to the heat exchange process and is associated with a larger heat exchange surface area related to the unit of rejected heat.

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