

Chapter 7

Thermal Management of PEM Fuel Cells in Electric Vehicles

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Abstract The increasing number of fuel cell electric vehicles (FCEV) on the roads will considerably contribute to CO₂ emission reduction and reduction of harmful air pollutants of the transport sector. FCEVs are seen as the future “long distance” and “all purpose” alternative to existing pure battery electric vehicles. The general objective in the FC development is to significantly reduce the costs and system degradation in order to increase the market penetration of FC vehicles. In addition to that, a critical issue represents an adequate thermal management and demand oriented cooling of FCEVs to avoid safety issues, degradation and a decrease in efficiency during operation. Proton exchange membrane fuel cell (PEMFC) can only tolerate a small temperature variation. Two factors are critical when designing a cooling system for PEMFCs. Firstly, the nominal operating temperature of a PEMFC is limited to roughly 80 °C. This means that the driving force for heat rejection is far less than in an internal combustion engine. Secondly, nearly the entire waste heat load must be removed by an ancillary cooling system because the exhaust streams contribute little to the heat removal. Several technical research publications and patents regarding effective cooling strategies are reviewed in this chapter. In the beginning, the thermodynamic characteristics of the heat generation and cooling requirements in a PEMFC stack are discussed. This is followed by outlined advantages, challenges and progresses of various cooling techniques with focus on liquid cooling. Finally, further research needs in this area are presented.

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Nomenclature

BoP	Balance of Plant (Auxiliaries)
FC	Fuel Cell
GDL	Gas Diffusion Layer
HT	High Temperature
HX	Heat Exchanger
LT	Low Temperature
RDE	Real Driving Emission
PEM	Proton Exchange Membrane
ICE	Internal Combustion Engine
H ₂	Hydrogen
FCEV	Fuel Cell Electric Vehicle
EV	Electric Vehicle
HVAC	Heating Ventilation and Air Conditioning
PEMFC	Proton Exchange Membrane Fuel Cell

7.1 Introduction

The major challenges for future road transport and therefore the global automotive industry are (i) Enabling individual mobility, (ii) Reduction of the energy consumption and (iii) Decarbonisation. To meet these challenges, electric vehicles with battery and fuel cell technology will be the key enabler. Pure battery electric vehicles are suitable for smaller vehicles and short ranges (urban) whereas fuel cells are more appropriate for larger vehicles with longer ranges and higher power demand. This review focuses on the cooling requirements and techniques of proton exchange membrane fuel cells (PEMFC) for automotive applications.

A PEM fuel cell produces waste heat which amounts to slightly less than its electric power output, thus leading to an energy efficiency of about 60%. Moreover, PEM fuel cells can only tolerate a small temperature variation. Current PEM fuel cells operate in the temperature range of 60–80 °C.

Two factors are critical when designing a cooling system for PEM fuel cells. Firstly, the nominal operating temperature of a PEMFC is limited to roughly 80 °C. This means that the driving force for heat rejection is far less than in an internal combustion engine. Secondly, nearly the entire waste heat load must be removed by an ancillary cooling system because the exhaust streams contribute little to the heat removal. These two factors necessitate relatively large radiators in automotive fuel cell systems. Furthermore, providing space for the radiators and the associated air

handling ducts represents a significant design challenge. Up to 50% of the delivered energy must be released via the cooling circuit [1].

The heat management system must be designed in a well targeted manner that keeps the stack cool via a system as small and light as possible.

With the advantages of high power density, rapid startup and low operating temperature, the PEMFC is considered to be the most promising candidate for the next generation power source for transportation [2]. The development of reliable, efficient and cost-effective FCs will be achieved by radically new and innovative development steps and technologies, especially regarding durability and costs [3]. Although a very high energy conversion efficiency of PEMFCs, a significant amount of heat generated, approx. the same amount of heat than the electrical power output [4] has to be removed to avoid overheating of the critical components, especially the membrane. As mentioned above, the operation temperature range for current PEMFCs is usually from 60 to 80 °C. Higher temperatures could provoke the degradation of the membrane and decrease the performance of the stack [5]. Lower temperatures are not favorable for the reaction kinetics and may also cause flooding due to lower water saturation pressures at lower temperatures, which is a major concern from the water management perspective [6–8].

Reference [9] outlines, that a cooling system design has direct impact in meeting the durability, cost, and performance targets for commercialization.

The present work is aimed at promoting the development of more effective cooling strategies by presenting a critical review of the reported cooling techniques and systems.

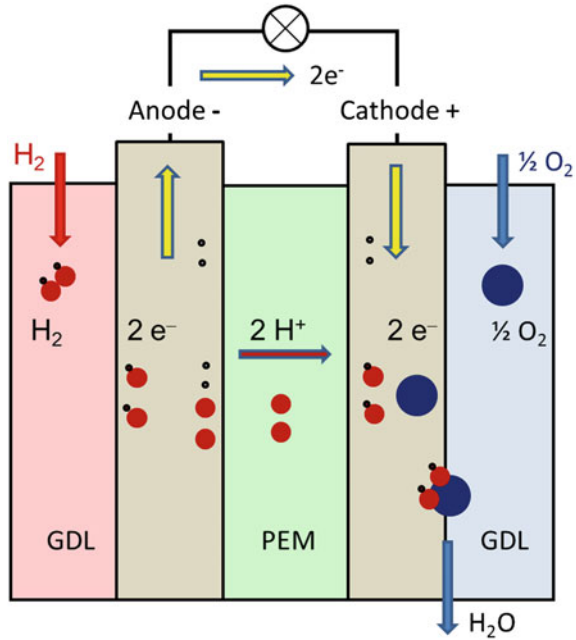
This review is sectioned as follows. Firstly, the thermodynamic characteristics of the heat generation and cooling requirements in a PEMFC stack are introduced. Then the advantages, challenges and progress of various cooling techniques with focus on liquid cooling are outlined. Finally, further research needs in this area are presented.

7.2 Functionality of PEMFC

The fuel cell as an electrochemical energy converter is able to directly convert the inner chemical energy of the fuel, usually hydrogen, into electrical energy. Thus the efficiency of the fuel cell is considerably higher than that of the combustion engine, where the conversion of the chemical energy first into heat is limiting the efficiency through the Carnot cycle. On the other hand the chemical processes of the fuel cell demand the use of catalysts and highly pure hydrogen, pressures, temperatures, and humidity have to be controlled within tight limits.

The scheme of a fuel cell is given in Fig. 7.1. Hydrogen is supplied to the anode via the GDL (gas diffusion layer). In an oxidation the hydrogen is split into protons and electrons there using a catalyst. The anode being the negative pole here supplies electrons to an electrical consumer. The protons cross the PEM (proton electrolyte

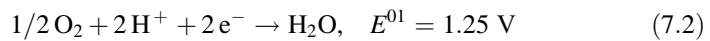
Fig. 7.1 Principle of PEMFC



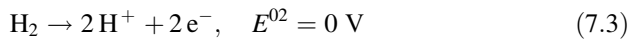
membrane) to the cathode. There oxygen usually from ambient air is reduced using a catalyst and with the protons yields water.



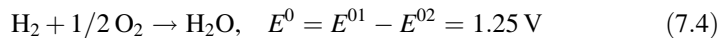
Reduction at the Cathode (Plus-pole):



Oxidation at the Anode (Minus-pole):



Resulting Redox-Reaction:



The thermodynamic characteristics of the fuel cell can best be explained using the voltage-current-diagram, see Fig. 7.2.

At standard conditions reaction (7.3) yields a reaction enthalpy of $\Delta_R H_m^0 = -241.8 \text{ J/mol}_{\text{H}_2}$ if the product water remains gaseous (lower calorific value). The negative reaction enthalpy divided by the number of electrons of the

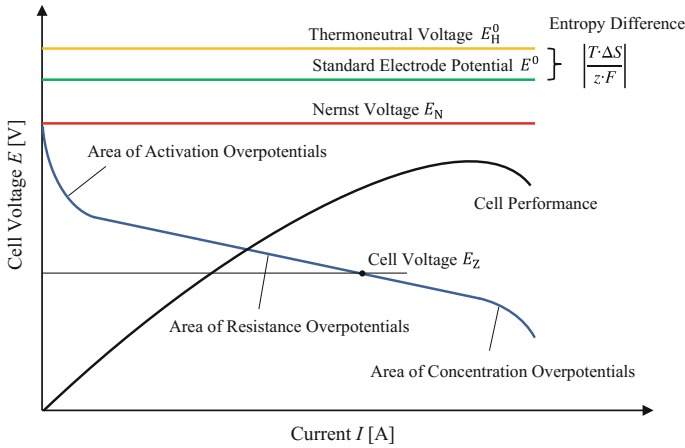


Fig. 7.2 Voltage-current-diagram or polarization curve

reaction z and the Faraday Constant $F = 96485.3 \text{ C/mol}$ gives the so called thermoneutral voltage $E_H^0 = 1.25 \text{ V}$. Only the free reaction enthalpy $\Delta_R G_m^0 = \Delta_R H_m^0 - T \Delta_R S_m^0 = -228.6 \text{ J/mol}_{\text{H}_2}$ can be converted into electrical work, which corresponds to the standard electrode potential $E^0 = 1.18 \text{ V}$. The difference $T \Delta_R S_m^0$ quantifies the heat loss to the surroundings. If real temperature and pressure conditions are taken into account, the standard electrode potential E^0 is reduced to the so called Nernst voltage E_N :

$$E_N = E^0 - \frac{R_m \cdot T}{z \cdot F} \cdot \ln \frac{a_{\text{H}_2\text{O}}}{a_{\text{H}_2} \sqrt{a_{\text{O}_2}}} \tag{7.5}$$

a is the activity (corresponding to the partial pressure with the ideal gas), $R_m = 8.3145 \text{ J/mol}$ the ideal gas constant. The theoretical thermodynamic efficiency of the fuel cell is given by:

$$\eta_{\text{th}} = \frac{\Delta_R G_m^0}{\Delta_R H_m^0} = 1 - \frac{T \Delta_R S_m^0}{\Delta_R H_m^0} = \frac{E^0}{E_H^0} = 0.945 \tag{7.6}$$

This value of 94.5% thermodynamic efficiency for the PEMFC applies at standard and idle conditions with no current flowing. If a current is applied, the stack voltage is reduced by a number of irreversible losses like the activation over-potential, the resistance over-potential and the concentration over-potential.

Practically the fuel cell is operated in the range of the linear resistance over-potential yielding a cell voltage E_Z .

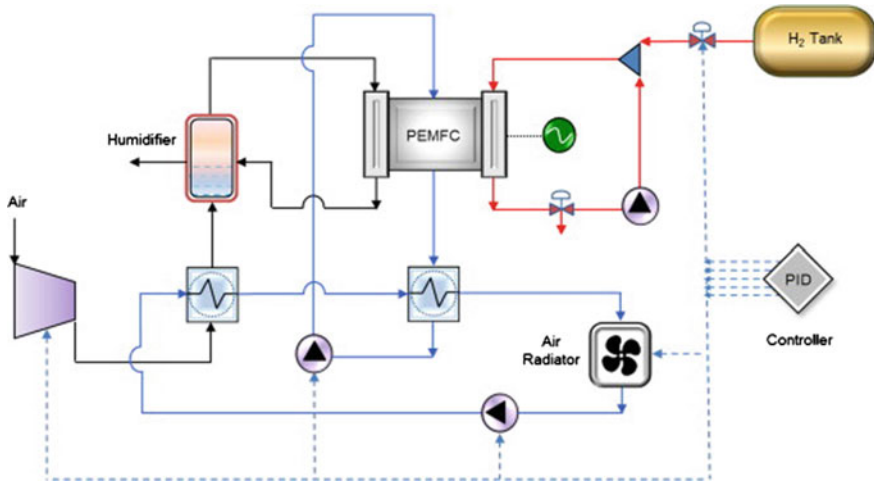


Fig. 7.3 PEMFC system [19]

The practical cell efficiency is given by the relation of the cell voltage E_Z to the thermoneutral voltage E^0 :

$$\eta_Z = \frac{E_Z}{E_H^0} \quad (7.7)$$

In practice the efficiency of a single PEMFC can reach values of up to 70% [10]. As the voltage of the fuel cell is limited, a number of cells are combined to form a fuel cell stack. This poses a number of challenges, as pressures, temperatures, and mass flows of the media have to be controlled within tight limits. In order to operate the fuel cell stack properly, it is necessary to control a number of auxiliary components (balance of plant—BoP). Figure 7.3 gives an overview of these components consisting of the hydrogen supply system and the air/oxygen supply system, water and thermal management systems, and the control unit. The air supply system consists of an air filter, an air blower or compressor, and a humidifier. The water and thermal management system controls the temperature and the humidity of the fuel cell stack.

7.3 Characteristics and Heat Transfer of PEMFC

The achievement of higher efficiencies with PEMFC systems represents a key aspect in order to enhance the market share of fuel cell electric vehicles. In principle, the overall efficiency of a PEMFC system depends on the stack characteristics (see polarization curve in Fig. 7.2) and the respective power consumption of the

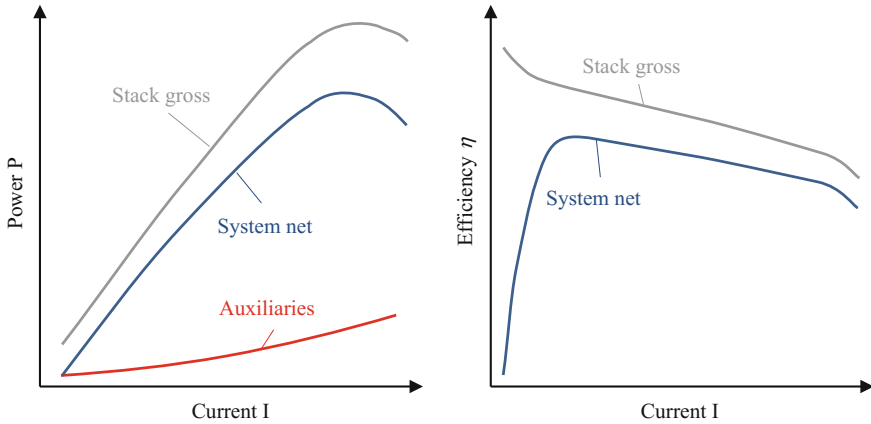


Fig. 7.4 Power and efficiency characteristics over electrical current

required auxiliary systems the so called BoP-components (air compressor, water pump, radiator, H_2 recirculation pump, etc.). Figure 7.4 presents the power and efficiency characteristics versus electrical current. The stack power is basically determined by the polarization curve. Stack power increases with higher electrical current until the maximum is reached. A further increase of electrical current results in lower power as the voltage of the polarization curve decreases drastically.

Overall fuel cell system net power results from stack power minus required power of auxiliaries. Present FC stacks achieve a power density of up to 3.1 kW/dm^3 by volume and 2 kW/kg by mass [11]. A further enhancement is the objective of many research projects. Moreover, a reduction of power consumption of auxiliaries is required and different concepts of BoP-components are investigated. The power consumption of the auxiliaries usually shows an exponential trend on electrical current. Main power consumer of the auxiliaries is the air compressor which compresses the air from ambient to cathode operation pressure of the stack. Cathode operation pressures usually range from a few mbar to 2000 mbar excess pressure and over-stoichiometric air-to-fuel ratios around 1.5–2.5 are generally applied. Basically, higher air pressure on the cathode side and higher air mass flow result in increased operating voltage at any particular current which further enhances stack gross efficiency. Nevertheless, the increase of stack efficiency is often repealed by lower mechanical efficiency as higher power is required for the air compressor. The mechanical efficiency considers the efficiency influence of the auxiliaries and represents the factor between stack and system efficiency. It is calculated by the power of system net to power of stack gross.

With PEMFC the stack efficiency is highest at very low electrical currents (part load operation) and decreases almost linearly with increasing current. By contrast, system net efficiency is lowest at very low electrical currents as the influence of auxiliaries is predominant (low mechanical efficiency). Highest system net efficiency is achieved in part load conditions with values up to 60% [12]. At very high

electrical currents system efficiency decreases again. Hence, many operation strategies of electric vehicles aim to shift the operation point to highest efficiency area by hybridization with batteries.

Despite the high system efficiency of fuel cells, high amounts of waste heat energies have to be transferred from the system. 5–15% of the energy input to the FC is lost as waste heat through the exhaust and 40–45% of input energy is converted to heat and transferred to the coolant system. Hence, the amount of heat is only slightly less than its electric power output.

Current PEMFCs operate in the temperature range of 60–80 °C. Basically, higher coolant temperature positively influences the polarization curve but the nominal operating temperature is limited to roughly 80 °C in order to avoid damages of the proton exchange membrane.

Figure 7.5 presents the heat flows inside a fuel cell system at a higher load point during a real-driving cycle. In this load point ~43% of input energy is converted to heat and transferred to the coolant system. Depending on BoP-system configuration

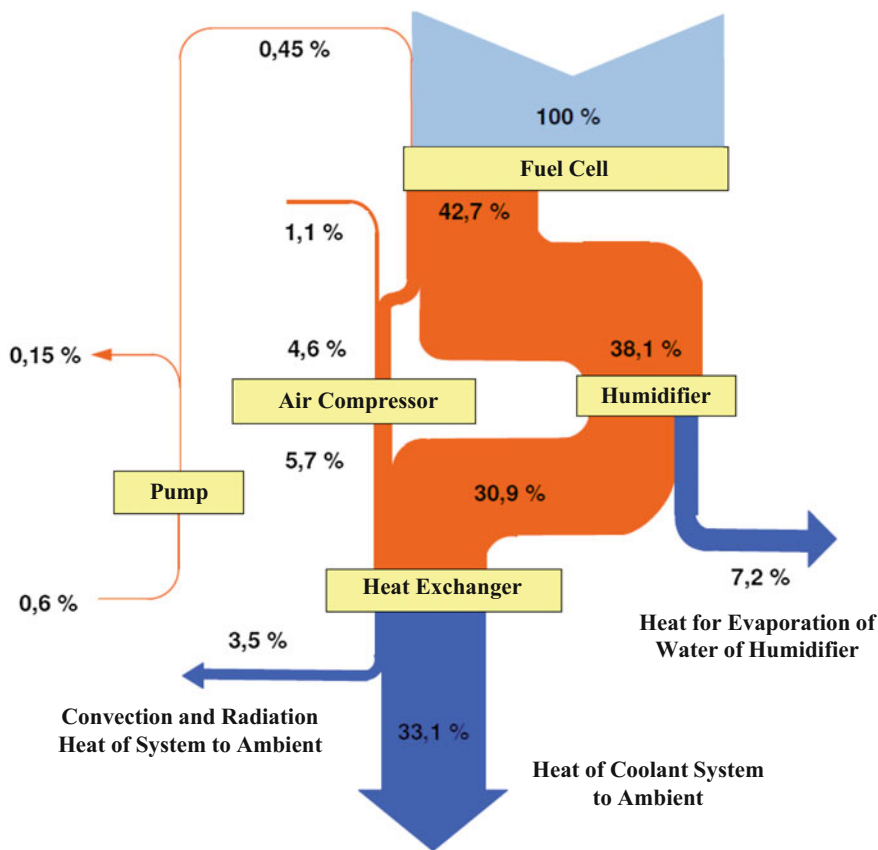


Fig. 7.5 Heat flows at higher load point during real-driving cycle [20]

some parts require cooling or use heat for a proper function. The shown system uses an external humidifier for humidification of cathode air. For evaporation of the water approximately 7% of input energy is required as heat. Present automotive systems try to avoid external humidifiers for efficiency and cost reasons [13]. Hence, higher amount of heat has to be transferred by the heat exchanger. Moreover, air compressor and pump also deliver heat to the coolant system. Overall 33% of the input energy has to be transferred as heat to the ambient by the heat exchanger.

These relatively low coolant temperatures in combination with the high amount of heat necessitate relatively large radiators in PEMFC electric vehicles. This represents a significant challenge regarding packaging and aims for sophisticated thermal management systems.

7.4 Cooling Requirements and Techniques Within a PEMFC Automotive

A typical low-temperature PEMFC with working temperatures clearly below 100 °C has an efficiency of up to 60% as mentioned before. As there is hardly any natural rejection of heat (which is minimum 40% of energy input like shown in Fig. 7.5) via exhaust gases various methods for the dissipation of the heat have been applied in the past. The following list gives an overview of the different approaches. The values in the brackets represent the FC power class for the proper approach.

- Cooling with cathode air flow via natural and forced convection (<300 W)
- Separate Air Flow (<2 kW)
- Heat spreaders also called edge cooling or passive cooling (<5 kW)
 - With highly conductive materials
 - With heat pipes
- Water cooling, using sensible heat of the coolant (>5 kW)
 - Deionized water, requires an ion exchanger
 - Antifreeze/coolant, lower heat capacity than pure water
- Phase change cooling, uses latent heat of the coolant
 - Evaporative cooling with water (500 W < 75 kW)
 - Cooling via boiling requires media with low boiling temperature (e.g. 1 kW)

Due to the power classes of an automotive PEMFC (>50 kW) and in terms of practicality the only reasonable solution with wide experience is the water cooling, to which deeper insight is generated via this chapter.

As medium either water or a water/glycol mixture is used for liquid cooling. The use of water in liquid cooling of a FC has the advantage of the very high specific

heat capacity of 4.182 kJ/kgK compared to air with 1.005 kJ/kgK and 50/50% water/glycol with <3.5 kJ/kgK.

Special attention in water cooling must be given to the electrical conductivity of the water/coolant. As the conduction in coolant can lead to current leakage in the stack or degradation of the bipolar plates the electrical conductivity has to be reduced. This can be either achieved via an ion-exchange resin or partly with filters with activated carbon particles or inert gas injection to purge oxidation products from the coolant.

The cooling channels for the water are integrated in the bipolar plate (see Fig. 7.6). The bipolar plate is the outer structure of the PEMFC and has several functions like the heat transfer from the MEA (Membrane Electrode Assembly) to the cooling circuit. In order to meet with these requirements, the conductivity must

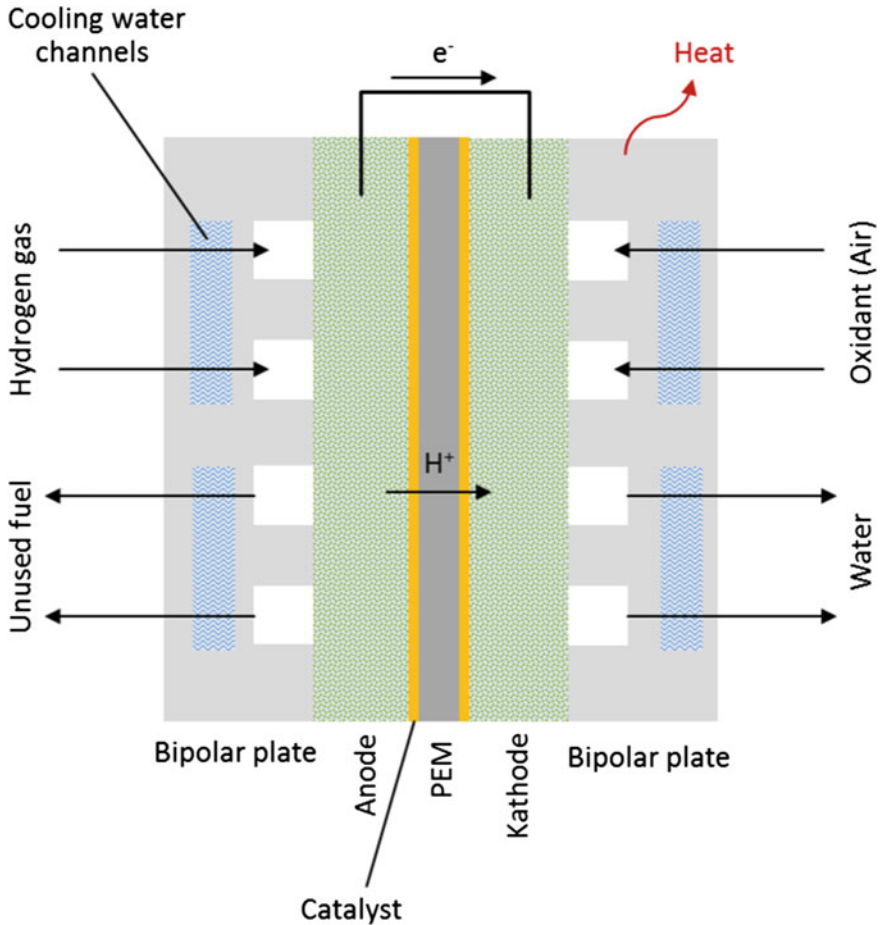
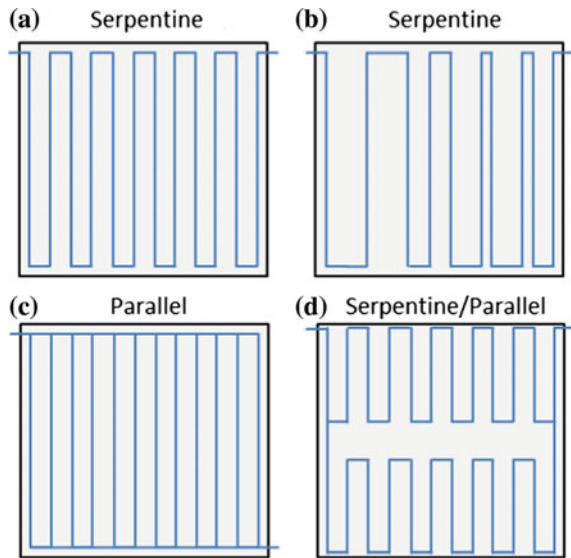


Fig. 7.6 PEMFC Architecture with cooling channels

Fig. 7.7 Different cooling flow field design in a fuel cell bipolar plate



be as high as possible, this can be achieved by the non-corrosive and commonly used graphite.

In terms of efficiency and durability it is highly favorable to keep the temperature uniform across the MEA. A uniform temperature profile across the stack was topic of several investigations [1] (Fig. 7.7).

These significant efforts—devoted to improve cooling flow field design—all came to the result that the serpentine design has a much better distribution of coolant flow.

Beside of a good uniformity of temperature the pressure drop must be kept low. Corresponding to several investigations it can be said that the parallel design goes along with lower pressure losses whereby the tradeoff (heat uniformity vs. pressure losses) can be seen as further optimization potential.

Next to the optimization of liquid coolant flow field design, also the coolant channel geometry can be arranged in order to gain better conductivity between die the bipolar plate and the coolant.

Reference [14] developed a so called chaotic 3D channels with chaotic laminar flow inside the channels. It is reported that the efficiency is much higher due to Nusselt number 4–7 time higher by even lower pressure losses.

Another approach was established by Honda, namely the V flow stack structure. While the hydrogen and air is transmitted vertically, the coolant flows horizontally across the bipolar plates. According to Hondas statement the cooling layers could have been reduced by its half and the weight density output could have been increased by 67%. This method has led to a significant reduction of weight and size of the PEMFC stack [15] (Fig. 7.8).

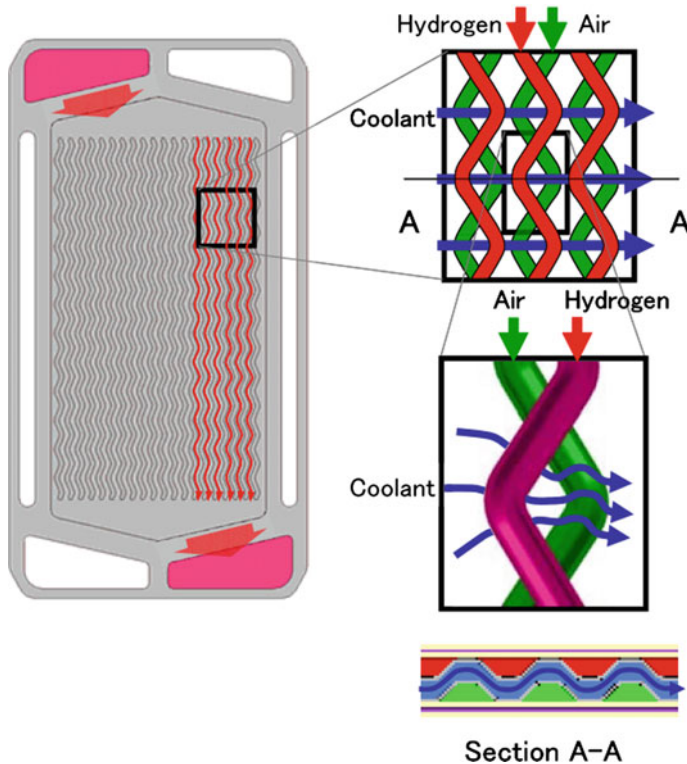


Fig. 7.8 Honda's PEMFC stack cooled by wave flow channels, copyright [15]

7.5 Cooling Circuits and Comprehensive Thermal Management

Beside of an adequate cooling channel layout the circuit architecture of the cooling system must be chosen. The system design of the BoP has a significant impact towards the efficiency of a PEMFC and the electrical power consumption of the auxiliaries. This system influences the parasitic vehicle power consumption as well as the size and weight of the stack.

In the following 4 diagrams different proposals for a cooling circuit for a PEMFC are given.

Concept 1 is to be seen as the most common approach, see Fig. 7.9. This system is also called 2-circuit system as there is one low temperature (LT) cycle for the e-motor and the power electronics, whereat especially the latter is in need of lower coolant temperatures which doesn't allow any satisfying use of one overall circuit architecture. The second circuit serves for cooling the stack and is called high temperature (HT) circuit. The system is driven by an electrically controlled pump; a particle filter can be used to avoid fouling of the PEMFC and the HX. Then the

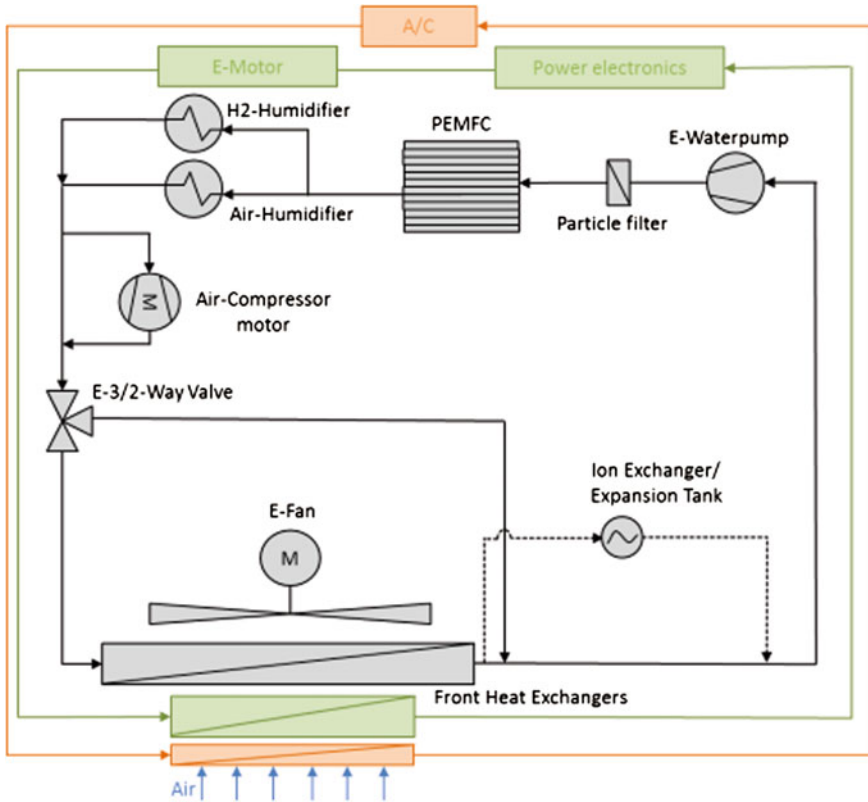


Fig. 7.9 Concept 1, conventional cooling circuit for a PEMFC

temperature control of the humidifiers is common with the release of heat prior absorbed from the FC. In a next step the compressor, respectively the intercooler (if existing), for the reactant air is conditioned. Via convection at the radiator the heat is released to the ambient air. Subsequently an ion exchanger is used in case of no use of glycol within the cooling circuit. This assembly ensures to reduce i.e. soda-ions and restock the water with potassium-ions. For this reason the water loses most of its electrical conductivity.

Concept 2 comprises of a second water circuit and an internal water/water HX, see Fig. 7.10. In the course of this architecture the control of the heat release is made by the pump control in the second circuit and not via a thermostat valve which is left out. The two-circuit-solution makes it possible to implement elements like the humidifier, air compressor or intercooler either in the internal or even in the external circuit. With this higher degree of freedom the components can be positioned in the most favorable temperature zone (inner circuit has a higher temperature level). This allows a more specific layout design and opens up new possibilities for tailor made solutions. Certainly, it must be mentioned that this advantages go along with more complexity and significant increase of weight.

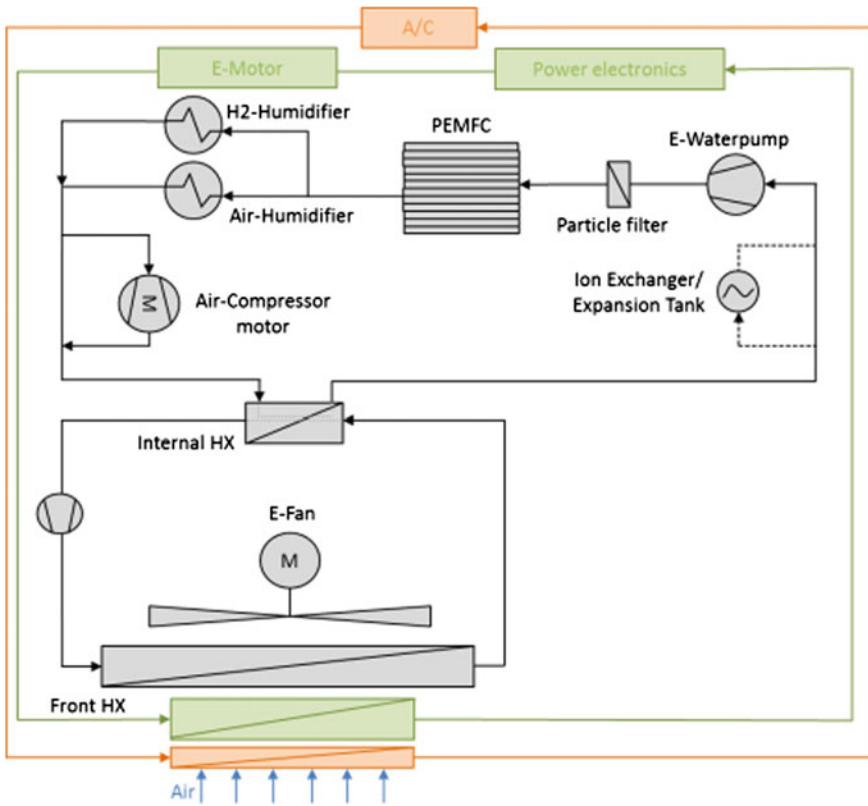


Fig. 7.10 Concept 2, PEMFC cooling circuit with a second HX

Concept 3 comprised of a waste heat recovery system which realizes to reuse the rejected heat and increases the thermodynamic efficiency of the PEMFC-system, see Fig. 7.11.

Reference [16] shows a feasibility study with different cooling agents, namely R123, R245fa and R134a, water and ethanol. This combined heat and power solution was investigated via ex situ tests whereat the PEMFC was loaded with constant current. The feasibility has been proved while obtaining an additional 4% in thermal efficiency of the overall system.

Concept 4 shows a novel approach for increasing the cooling efficiency of the HT-cooling circuit of the FC, see Fig. 7.12. By the use of an additional heat exchanger between HT- and LT-circuit respectively HT- and A/C-circuit extra cooling performance can be gained. On the one hand, this goes along with higher (and for FC very important) cooling performances; on the other hand this leads to an increase of the total system efficiency because of better utilization of the proper cooling capacities. It is required to execute vast prior investigations towards

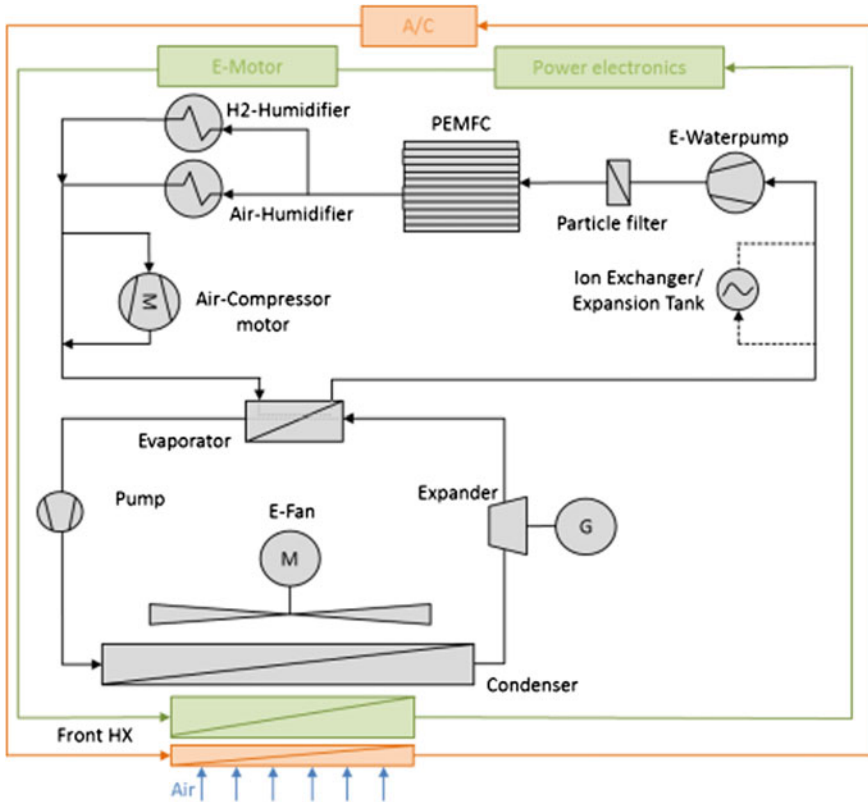


Fig. 7.11 Concept 3, PEMF cooling circuit with ORC for waste heat recovery

control—and operation—strategies in order to have a resilient validation for the temperatures in the cooling/conditioning cycle.

The prior concepts all consist of a pump, a fan, a radiator and a valve. In order to optimize the system in general suggestions are made in the following (valid for all 4 concepts, mentioned above).

7.5.1 Pump

Two control circuits for the pump are proposed. On the one side the pressure of the coolant shall be controlled, on the other side the temperature difference at in—and outlet of the stack shall be kept constant in operation.

Pressure differences between coolant, H₂ and air must be avoided as a matter of principle in a FC for adequate operation. Especially in cases of purging (cyclic, emptying of H₂) the pressure in the system significantly decreases. At the same time

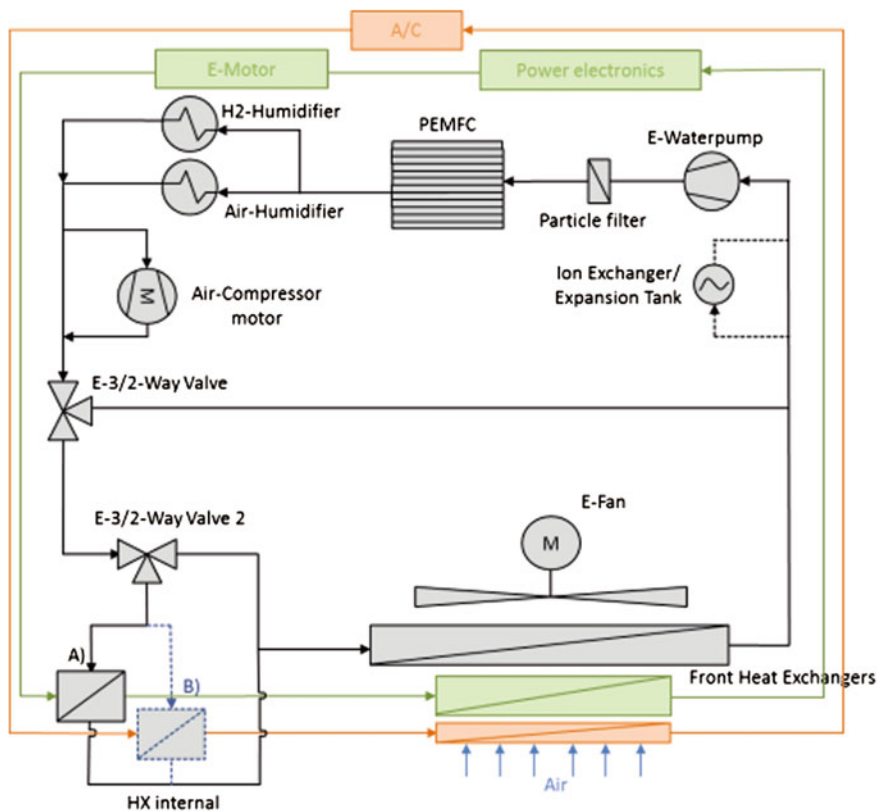


Fig. 7.12 Concept 4, PEMFC cooling circuit with additional HX with A/C or LT-circuit

the pump power control of the pump must be lowered. Pressure difference between the coolant and gas (H_2 as well as air) must be kept below 50 kPa.

The second control keeps the temperature difference between inlet and outlet of the stack module in a defined range (usually between 4 and 7 K). This measure is to be done for a highest uniformity of the temperature profile within the stack. This temperature control superimposes the pressure control. Together with the valve and fan control the stack temperature profile can be kept within the specified temperature regions for low degradation and high efficiency.

7.5.2 Fan

The fan shall be integrated via a hood to avoid leakage flow beside the heat exchangers (HXs). Like the electrical water pump, the fan shall be driven by stack module voltage (300–450 V). It shall consist of an electric control which enables

the fan when too high temperatures occur in the stack module. Especially events like stop-and-go and mountainous routes require major cooling capacity, whose power consumption can be kept low via intelligent control strategies.

The increase of more air volume by more power is limited because the increase of the volume involves the rise of power consumption with the factor three. The pressure characteristic of a fan shall be as flat as possible which means that in the fan's downtime nearly no influence towards the dynamic pressure (natural stream) shall be given (overblowing of fan).

7.5.3 Valve

As valve a wax thermostat with a temperature depending characteristic can be used. Though, it is recommended to use an electronic controlled valve, which allows more flexibility in terms of different conditioning modes. Especially in system 4 in Fig. 7.12 the two proposed valves are used for specific cooling strategies which require fully controllable valves with a proportional way characteristic.

7.5.4 Radiator

The radiator is the main component in response for the convection of heat. As the coolant inlet temperature of the FC has to be below 80 °C the requirements for heat dissipation are much higher than with combustion engines. Therefore the enlargement of the HX is highly favorable. Experimental as well as computational studies [17] revealed the high influence of the HX-size, whereat optimized radiator sizes increase the heat rejection with more than 50%.

One interesting solution towards optimum air velocity may be to install one big HX with two fans which cover the major surface of the radiator. The fans shall have a very steep characteristic, at which the HX is configured for maximum heat release with fan operation.

In order to allow heat rejection in low operation modes an additional HX is applied at the very front end which is not subject to the steep fan characteristic and allows a high dynamic pressure operation.

Evaluation of cooling system components with the interaction of the PEMFC can be made either via experimental tests or via simulation. As the simulation is more cost efficient experiments shall be made solely for the validation.

For example an analytical evaluation via one-dimensional modeling can be examined. This concludes the multi-zone calculation of the thermal network, each zone representing physical and chemical phenomena's for the appropriate illustration of hydraulic and thermic behavior. The heat source, namely the PEMFC, can be modelled with a phenomenological method (1D), quasi dimensional method (0D) or non-dimensional method like neuronal, polynomial and mean value models.

The heat release from the FC is transferred to the cooling circuit, whereat interactions between the water circuits and the fuel cell are shown. This allows the optimization of the cooling circuit with respect to optimum FC-temperatures with the possibility of investigating different ambient conditions and road profiles. Especially mountainous roads with steep inclinations and at the same time at very high ambient temperatures have to be subject to benchmarks, not only for the optimization but even for a component protection. Here, the simulation offers wide varieties and a fast acquirement of results with low expenditure.

7.6 Conclusion/Further Research Needs

High power requirements of PEMFC stacks while limited space at automotive applications are the significant challenges for a cooling system for FCEVs.

The problem becomes more severe due to the small temperature difference between the PEMFC stack and the ambient air, and an almost negligible heat removal by the product streams. The heat generation, its removal and the resulting temperature distribution within the cell components directly affect the interfacial properties, local heat generation rate, and water transport [18].

A number of cooling strategies and techniques have been developed and applied in practice for PEMFC stacks with different power ratings. These cooling strategies are summarized in this article. As reviewed in this work, significant advancements have been made in cooling of PEMFC stacks.

Liquid cooling has been widely and successfully applied in automotive PEMFC stacks.

7.6.1 Further Research Needs

It is evident, that a cooling system design has direct impact in meeting the durability, cost, and performance targets to promote their commercialization under wide range of ambient conditions, from high ambient temperatures to extremely frigid conditions in colder climates [9].

Some of the future issues are summarized below [18]:

- Fundamental understanding of the thermal properties and heat transfer characteristics of PEMFC components through in situ and ex situ experimental investigations.
- Optimization of the coolant and reactant flow configurations to achieve the desirable distribution characteristics of local current density, temperature and water content in the PEMFC at low cost and improved efficiencies.
- Improving heat transfer efficiency of radiators for automotive PEMFC stacks to reduce their sizes.

- Developing a coolant that has a high ionic resistance, does not degrade over the lifetime of the stack, and has a low viscosity for reduced pumping power.
- Further improvements by adaptation of the circuit design—like shown in the 4 concepts (Figs. 7.9, 7.10, 7.11 and 7.12), to increase the heat rejection. Especially the coupling with the HVAC system, which can generate considerably more cooling performance, shows high potential.
- The use of heat accumulators inside the cooling system to stabilize the temperature.
- Sprinkling of condensed water from exhaust gas to improve cooling performance of a radiator by evaporation of water (also known in diesel plants with two-stage turbocharging and intensive water condensation in an intercooler).
- Further increase of stack efficiency and enhancement of coolant temperature.

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