Current Trends in Automotive Fuel-Cell Air Management Systems

Aktuelle Trends bei Brennstoffzellen-Luftversorgungssystemen

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Abstract

In this paper the design and function of modern automotive fuel cells and their air supply systems are presented.

After a brief introduction into the basics of fuel cells and fuel-cell-systems the first part of the paper focuses on up-to-date information about "hard" system-requirements (e.g. mass-flow, pressure-curves…) and additional "soft" requirements (e.g. noise emission, air quality) to be met by the air management system. This is especially important as most of the data published until today is largely superseded by advances in fuel-cell technology.

In the second part of the paper emphasis is put onto the discussion of potential technical solutions for the realization of an air-management system fulfilling these requirements and a system designed following these considerations is presented, giving an insight into some innovative details.

1. Introduction

Fuel Cells (FC) for automotive applications offer a variety of unique features compared to conventional internal combustion engines. Namely zero-emission capability and high system efficiency potential explain the world wide efforts made by all major car manufacturers to develop fuel cell systems as future power sources for clean and efficient mobility based upon a developing universal hydrogen infrastructure.

The oxygen needed for „cold burning" of hydrogen within an automotive fuel cell in order to generate electrical energy is taken from atmospheric air which is pressurized and, in some cases, humidified, by the so called air management system. This system might also comprise an expander to recuperate exergy in the off-gas behind the fuel cell stack.

For several reasons, the air management system is one of the most critical peripheral systems:

- High power demand of up to 25% of the total generated electrical power,

- Interface between environment and fuel cell (humidity, dust, hydrocarbons, other gaseous compounds like sulphur, carbon monoxide, chlorine, etc.),
- Major source of sound emission from FC system,
- Limiting factor on system dynamics.

Screw compressors are among the first choices of machinery for FC air management systems, necessitating a closer look upon the specific requirements for air management systems. Besides optimization of geometry, specific weight and -volume, the generation of high quality compressed air free of residual hydrocarbons, particles and metal ions must be ensured. Moreover, the instationary dynamics of the air management system governs to a large extent the overall dynamics of the fuel cell system, implying a variety of tasks in pressure and mass flow control.

2. Fuel-cells working principle

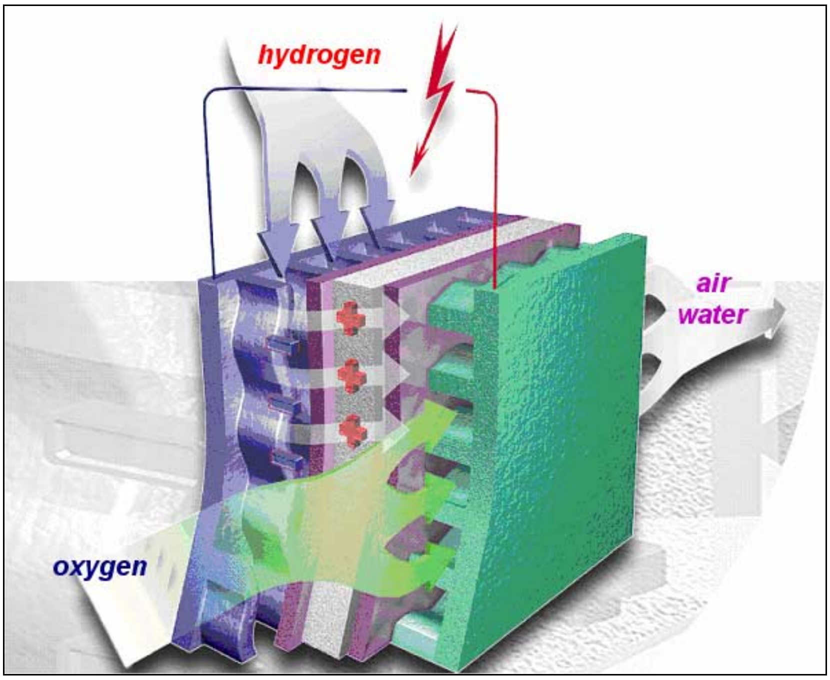

Figure 1: Basic structure of a PEM fuel cell

The basic principle of a fuel cell has been developed by the British physician Sir William Robert Grove in 1839. It is based on the concept of the electrolysis of water running in the opposite direction, combining hydrogen and oxygen to generate water and electricity.

The first time the principle was extensively put into use was during the 1950‘s in the NASA space program.

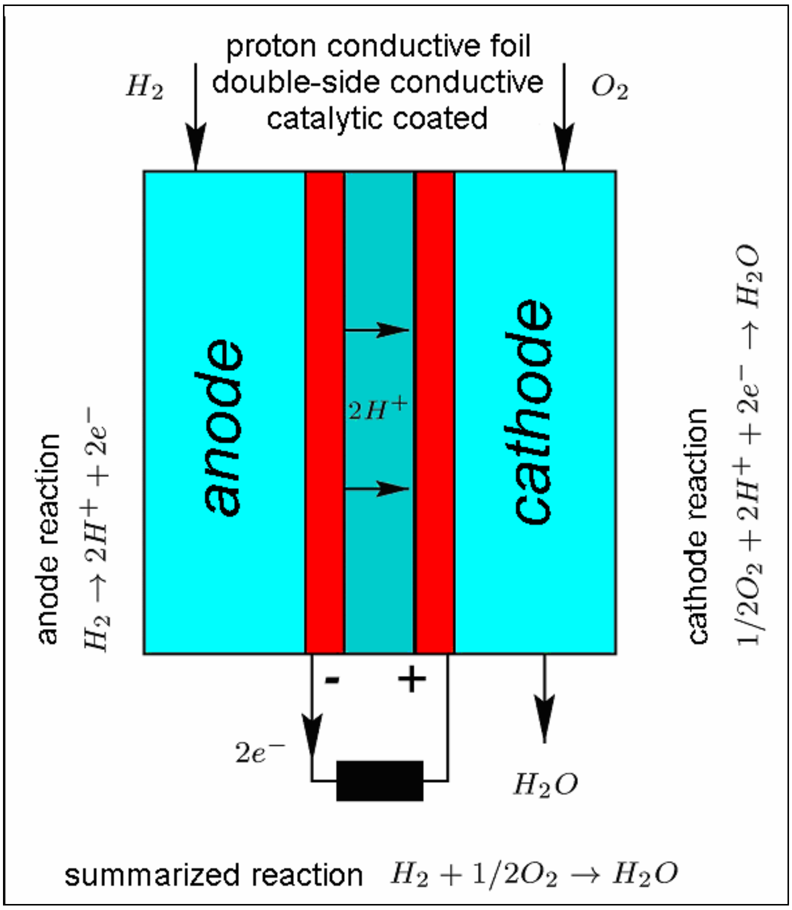

Figure 2: Chemical reactions in a PEM fuel cell [1]

In a fuel cell hydrogen and oxygen react in a controlled so called „cold burning“ reaction. The basic layout of a PEM (Polymer Electrolyte Membrane) fuel cell, the type mainly used in transportation applications, is shown in **Fig. 1**. Hydrogen and oxygen flow through ducts in the so-called bipolar plates. The streams are separated by the proton-permeable membrane. At the anode-side hydrogen is ionized using a catalyst:

$H_2 \rightarrow 2H^+ + 2e^-$.

The protons pass through the proton conducting membrane while the electrons remain there. As a result the anode obtains a negative charge.

The electrons can reach the opposite (cathode) side through an external electrical circle, forming an electrical current.

At the cathode side oxygen, hydrogen ions and electrons recombine and form water:

$$1/2O_2 + 2H^+ + 2e^- \rightarrow 2H_2O.$$

Fig. 2 gives an overview over the chemical reactions involved.

There currently are five basic types of fuel cells, distinguished by the electrolyte used. Their characteristics and process parameters differ significantly. **Table 1** shows a comparison of the different types and their main uses.

Table 1: Basic types of fuel cells

Type	**Electrolyte**	**Working temperature [°C]**	**Remarks**	**Main uses**
AFC (Alkaline Fuel Cell)	Alkaline	60-120	High efficiency, running on pure hydrogen and oxygen	Military, space
MCFC (Molten Carbonate Fuel Cell)	Molten carbonate	650	Corrosion problems, complex process	Power generation
PAFC (Phosphoric Acid Fuel Cell)	Phosphoric acid	150-250	Corrosion problems, low efficiency	Power generation
PEMFC (Proton Exchange Membrane Fuel Cell)	Proton conducting polymer	20-160	High power density, high flexibility, rugged	Automotive applications
SOFC (Solid Oxide Fuel Cell)	Solid Zirkonium Oxide	850-1000	Fuel tolerant, high efficiency	Power generation

Today the PEM fuel cell is the favoured system for automotive uses, offering high power density, good cold starting capabilities and dynamic behaviour.

3. System layout

To supply the fuel cell stack with the necessary reaction media and coolant additional components are necessary.

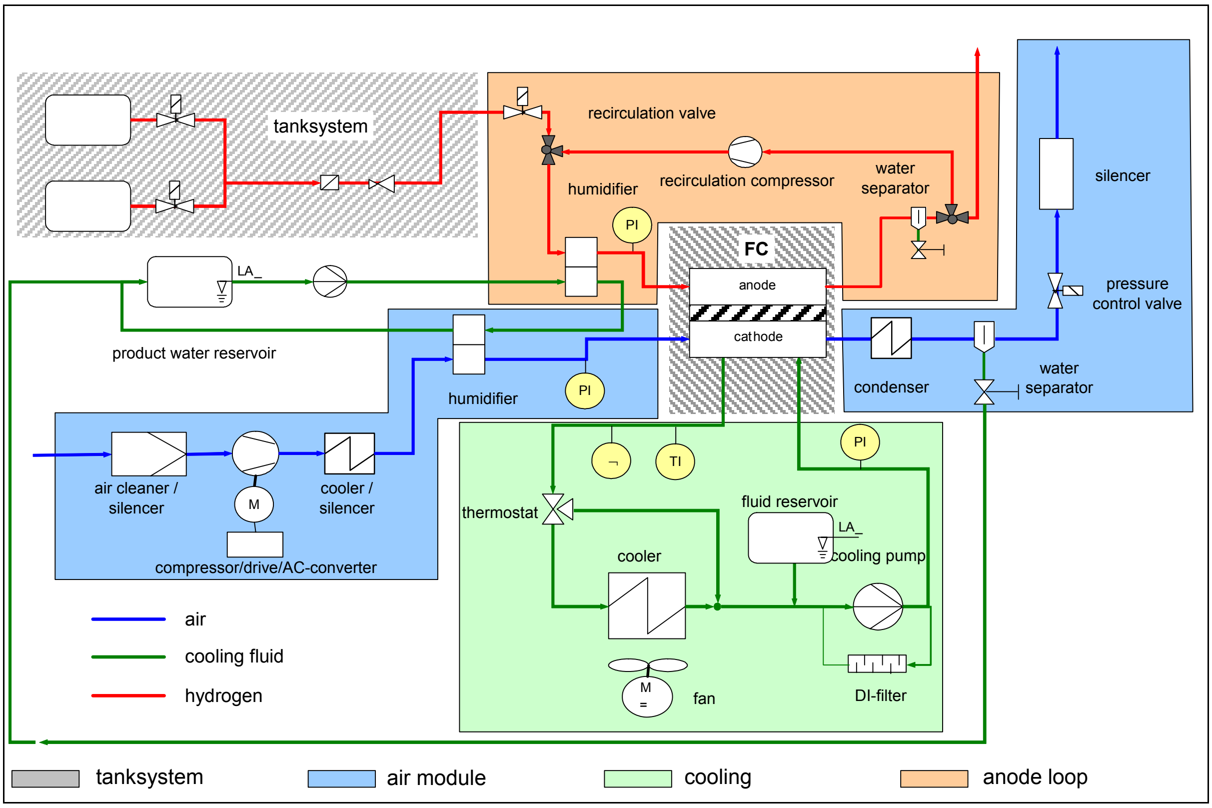

Figure 3: Schematic layout of a fuel cell system with main flow paths

Fig. 3 gives a schematic overview over a typical automotive PEM-fuel-cell system with the subsystems

- tank
- anode (hydrogen) system,
- cooling system,
- cathode (air) system

arranged around the fuel-cell stack.

The paper presented is focussing on the air subsystem.

The air enters the subsystem through the air filter which, unlike conventional air filters, usually incorporates additional chemical stages to eliminate gaseous contaminants potentially harmful to the fuel-cell stack.

It then enters the subsystem's main component, the compressor driven by a variable speed electric motor. After exiting the compressor the air is conditioned to the appropriate temperature and humidity by means of an intercooler and humidifier before entering the fuel cell stack.

The stack's offgas (basically air, partially depleted of oxygen, and water) is, depending on the humidification system, either sent through the other side of the humidifier or, as shown in Fig.

3, a condenser to recuperate water for the humidification-system and a pressure control valve. Additional components like resonators and silencers are used to improve the NVH[1]-performance of the subsystem.

4. Typical air-supply load-lines

Advances in fuel-cell stack design have allowed a considerable reduction of the cathode (air) side pressure over the last years.

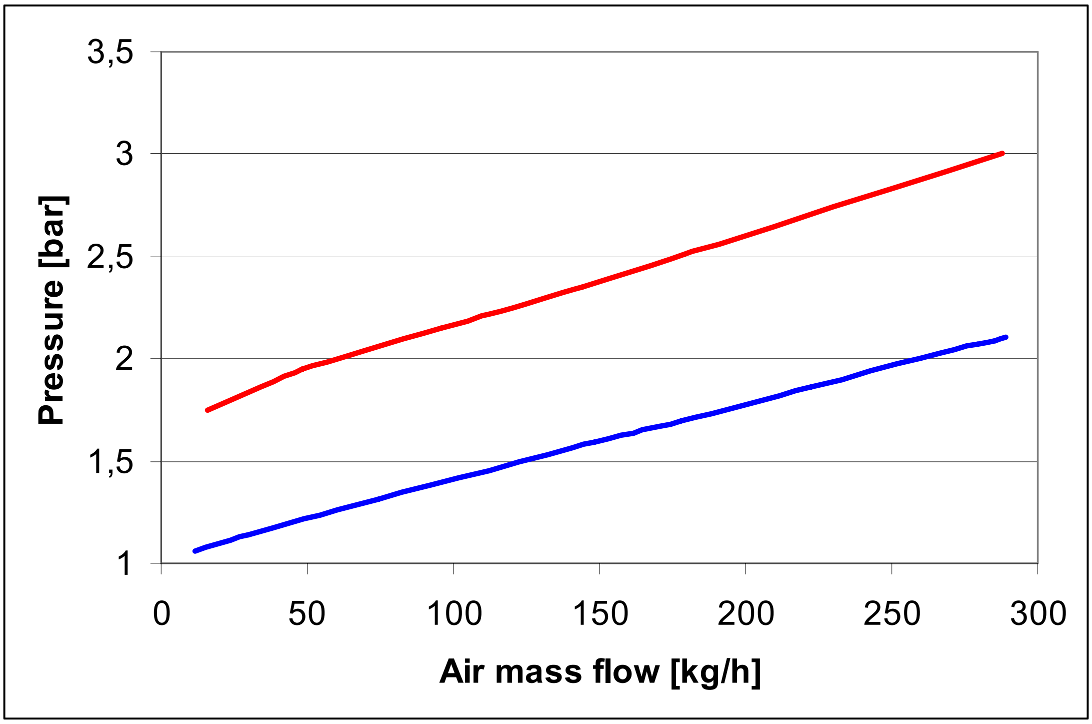

Figure 4: Typical fuel-cell air-pressure curves 3 years ago (red) and today (blue)

Fig. 4 shows typical pressure curves for fuel-cell stacks representing the technology in use ca. 3 years ago and today. As can be seen the general form of the curve has persisted, but the overall pressure has been significantly lowered.

This allows higher system efficiency because of the reduced parasitic losses caused by the compressor.

Nevertheless higher pressures can be advantageous under certain circumstances because higher power-densities can be achieved.

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[1] NVH: Noise, Vibration and Harshness

5. Hard and soft requirements

Based on current stack and system technology a basic set of requirements for a fuel-cell cathode-air compressor with integrated motor as core component of the air-management subsystem can be developed and is listed in **Tab. 2**.

Table 2: Basic requirements for a cathode-air compressor with integrated electric motor for the supply of 100 kW fuel cells [2]

Parameter	Min.	Typ.	Max	Dim.
Suction pressure	0,62	1,013	1,15	bar_a
Suction temperature	-28	20	50	°C
Pressure ratio	1,85		2,8	
Air mass-flow	18	324	360	kg/h
Isentropic efficiency (design-point)	0,65			-
Dynamic response time (10-90% mass-flow)			0,6	s
Coolant inlet temperature	-28		85	°C
Coolant volume flow			5	l/min

In addition to the „hard“ targets listed the components have to meet some less well definable requirements. Unlike conventional internal combustion engines (ICE) the electric drivetrain of fuel cell vehicles is basically silent, usually leaving the air compressor as the most prominent source of noise in the whole system. The disturbance created by the compressor's noise-emission should be reduced to a minimum by primary (e.g. design of ports…) and secondary (e.g. silencers and encapsulation) measures. The remainder of the radiation should have a spectral distribution not unpleasant to the human hearing.

Fuel cells are highly susceptible to damage because of contaminants in the cathode-air. Even small amounts of contamination can harm the catalyst coatings on the membranes, leading to performance degradation. The contamination can either result from contaminated suction air or from abrasion, leaks or corrosion by-products in the components itself.

Under today's ambient conditions the suction air is heavily contaminated by gaseous compounds like sulphur, carbon monoxide, chlorine and dusts. To make this air suitable for fuel cells it has to be treated to much higher standards than in conventional applications for internal combustion engines (ICE). With ICE's it is usually sufficient to remove dust particles by physical filtering, not dealing with gaseous contamination at all. Fuel cell air filtering systems have to use an additional chemical cleaning stage, removing these gaseous contaminations by e.g. charcoal filters, adding significantly to the complexity of the system.

The other major source of contamination lies within the air system components themselves, mainly because of oil leakages e.g. at shaft seals or abrasion. Any oil contamination will result in serious irreversible performance degradation of the fuel cell. Extensive measures have to be taken to avoid oil leakage into the airstream, either by fitting sophisticated sealing systems or by totally avoiding the use of oil or oil containing lubricants.

6. Exemplary technical solution

To meet all the given requirements screw-compressors and radial flow turbo compressors are considered to be the most promising options by fuel-cell system designers. Turbo compressors offer considerable advantages when it comes to size, weight and acoustic performance but still pose significant challenges because of the high rotor-speed involved. The available electric drives and bearings have not yet shown satisfactory performance under automotive conditions despite considerable effort by their developers.

VW has developed a prototype air supply module shown in **Fig. 5** in cooperation with specialized partners. Its main components are a screw-type compressor driven by an asynchronous electric motor, which is controlled by a DC/AC converter (inverter).

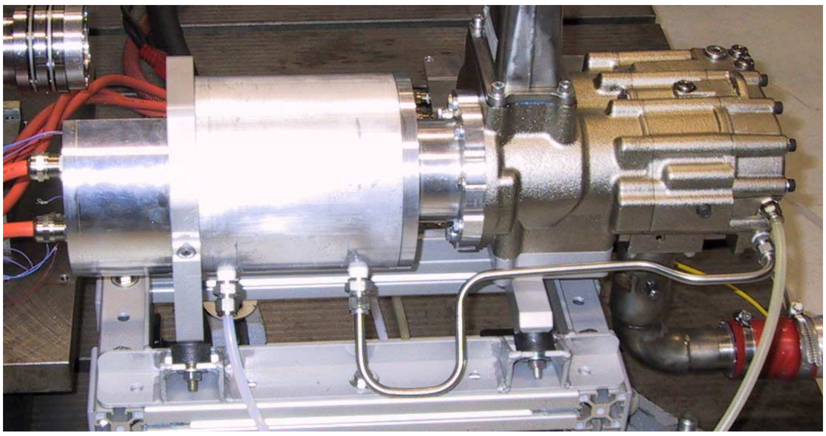

Figure 5: Picture of the air module developed by VW / SRM

The following paragraphs explain some of the technological features and design considerations.

6.1 Screw compressor

The main targets for the development of the new compressor, which is the core component of the air supply module, were defined as:

- Low noise emission,

- High efficiency over a wide range of mass-flow and pressure-ratios,
- High air quality.

The noise emitted by a screw compressor has three main sources:

- Gas pulsations at inlet and outlet side,
- Airborne noise emitted by the casing and other components,
- Structural noise, e.g. mechanical vibrations.

Through careful analysis the pulsations at the compressors outlet and, to a lesser extent, the inlet, which in turn attenuate other components, have been identified as a dominant factor.

To reduce the overall noise emission two basic concepts have been followed.

Primary measures focus on reducing the compressors raw emissions by minimizing pulsations, e.g. through careful design of ports. The unusually high number of rotor lobes (6+8) used in the compressor is advantageous from an acoustic point of view. First of all it results in a more uniform flow, reducing unwanted pulsations, secondly it moves the remaining excitations to higher frequencies, allowing reduced bulk and weight of secondary measures.

These consist out of resonators or mufflers and noise reducing encapsulation of critical components. To avoid the pressure losses associated with mufflers the use of tuned resonators is advantageous for the frequencies encountered in this specific case. By careful combination of several resonators, tuned to different frequencies, acceptable noise-levels and a spectral distribution of the remaining noise not unpleasant to the human hearing can be achieved.

Noise emitted by the compressor’s casing and structural noise can be reduced by covering the components in capsules made from insulating or dampening foam and the use of flexible mounts and careful decoupling of any rigid connections.

One key to high efficiency over a broad range of operation is the possibility to vary the internal volume ratio.

The vi-valve gives the ability to change the built-in volume ratio controlled by the outlet pressure of the compressor, leading to less power consumption by reducing the ‘over-compression’ when only low pressures are needed. As shown in **Fig. 6**, after the filling phase the internal compression phase is shorter with the vi-valve opened. The working chamber is connected earlier to the high-pressure side and the shaft work can be reduced.

A positive by-product is a reduction of the sound emission through reduced attenuation resulting from pressure-equalization flows.

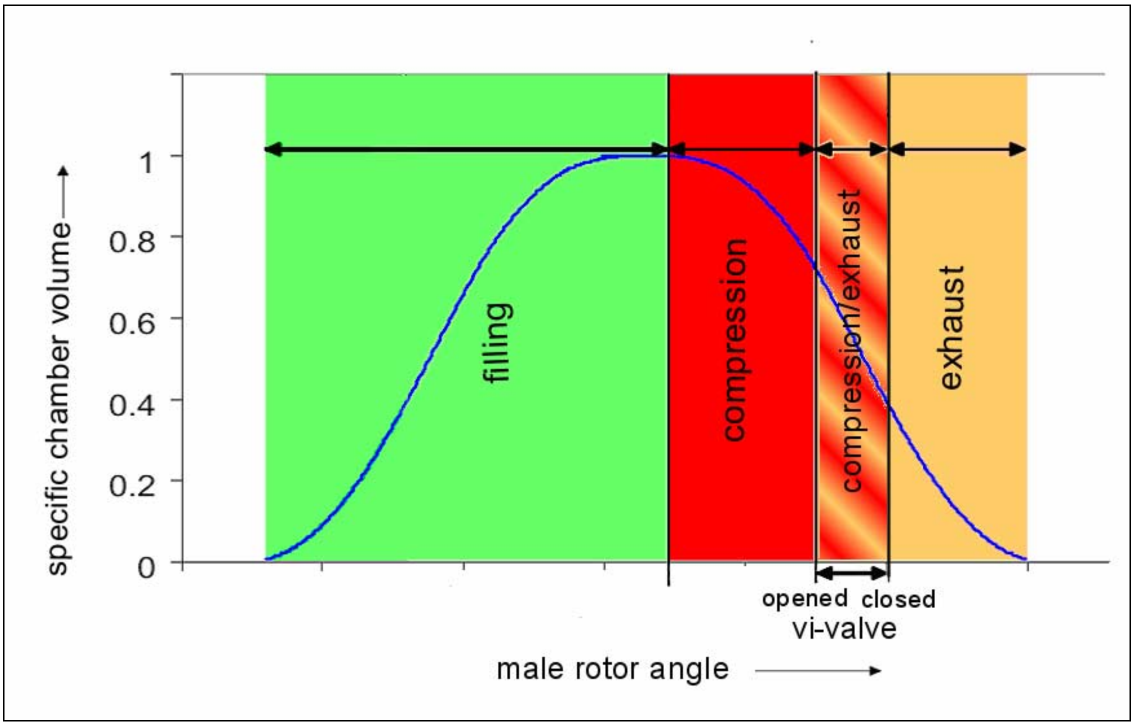

Figure 6: Volume curve for the compressor with a built-in vi-valve

As already mentioned, fuel cells are highly sensitive against contaminants in the cathode air. For that reason a multi-stage sealing system between working chamber and gearbox, consisting of double shaft-seals is used. Additionally, a pressure drop over the seal towards the gearbox helps the oil staying away from the working chamber. One of the great challenges is combining perfect sealing with low friction over the full designed lifetime and range of operating conditions while at the same time meeting the low cost-targets associated with automotive components.

6.2 Electric motor

The air supply subsystem for a typical automotive fuel cell has to deliver an air mass flow as seen in Figure 4, causing a power consumption of up to 15kW. Achieving the necessary power in the available package-space is an engineering-task in itself.

As no suitable supplier could be identified the motor has been designed in-house by VW, heavily building on experience from several earlier projects.

Despite the higher power-density achieved with permanent-magnet synchronous motors an asynchronous induction motor was adopted because of the simple and rugged design and lower cost.

The chosen motor elements offer a relatively high power density by using e.g. copper conductors in the rotor plus an advanced design of the stator. The maximum speed is

24000min^{-1}. The cooling fluid with a maximum inlet temperature of 85°C circulates around the outer hull of the casing in a spiral-like canal to dissipate the heat generated effectively.

6.3 Inverter

Fuel cells generate electric energy in form of a direct current, whereas an asynchronous machine needs alternating current. This conversion is done by an electric converter that generates AC power with a variable controlled frequency.
As no suitable automotive units could be sourced a new unit, based on the general concepts of an advanced commercial frequency-converter, has been designed by a specialized supplier. This converter has already passed severe tests for use in the automotive environment and offers some special features characteristic for automotive standards.
Water cooling through the inverters bottom plate makes it possible to arrange the power electronics in a space saving way without producing heat spots, possibly causing defects.
In newer days, automotive applications more and more use the standardized 'Controller area network' (CAN) to establish communication between components and their controller. The DC/AC converter has such an integrated CAN-Interface connected to the Fuel Cell controller via CAN-Bus, **Fig. 7** gives an overview over the electric implementation of the air module into the fuel cell system.
A general feature of automobile-electronics is their ability to withstand harsh environmental conditions like immersion, shock and vibration and extreme temperatures.

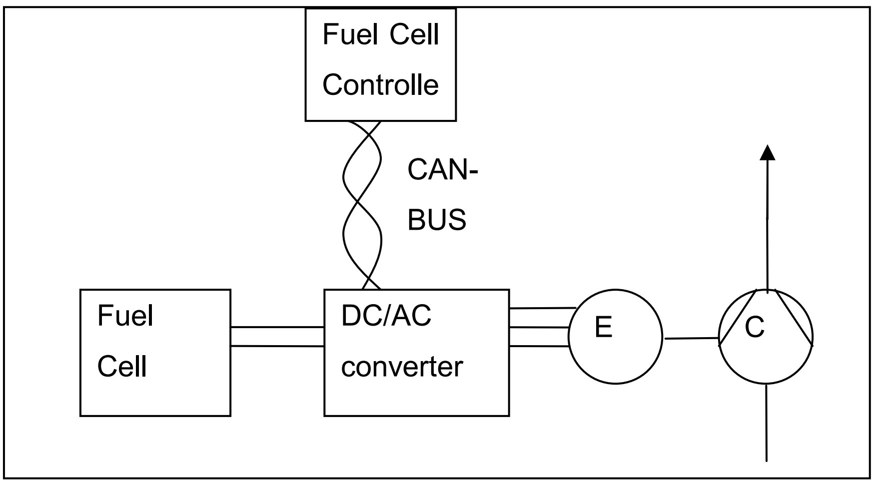

Figure 7: Schematic electric implementation of the air module components

7. Outlook

Main factors for automotive applications include the package, especially volume and weight, as well as the costs. That means, concerning the developed air-module, that further efforts go straight to a higher integration of yet more or less externally placed parts.

Currently, a coupling is used to connect the electric drive with the compressor. With an applicable bearing concept this coupling could be omitted. An overhung arrangement of the compressor or the e-drive leads to a decreased number of bearings and thus to a minimized installation space. Moreover, a reduced number of parts result in less design, manufacturing and installation costs for the whole module.

The acoustic components, namely the resonators, are yet installed as flanged parts to the module. For further optimization these should be arranged in a more space saving way, e.g. integrated into the duct near to the high-pressure port.

At last, even the electric inverter gives the opportunity for some more integration, e.g. with the use of ASICs (application specific integrated circuits) instead of the standard electronic components used.

8. References

[1] Kauder, K., Temming, J. *Luftversorgung für Fahrzeugbrennstoffzellen*. In: Schraubenmaschinen Forschungsberichte Fluidenergiemaschinen Nr.9, Universität Dortmund, 2001

[2] Hinsenkamp, G., Romba, M. *Requirements for Air Management Systems in Automotive Fuel Cells.* In: VDI-Berichte 1715, VDI-Verlag, Düsseldorf, 2002