# Requirements for Air Management Systems in Automotive Fuel Cells

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## Abstract

In the current paper, the design and function of modern automotive fuel cells and their air supply systems are presented. The demand for high customer performance of modern automobiles (high acceleration, range, comfort and fuel economy) results in the specification of typical soft requirements for the air management system within automotive fuel cells. Based upon different designs and alignments of major components, typical load lines for compressors and expanders are discussed and the key development goals for air management systems are identified.

# 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 universal hydrogen infrastructure yet to come.

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. In many cases, this system also comprises 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 sulfur, carbon monoxide, chlorine, etc.)
- Major source of sound emission from FC system
- Limiting factor on system dynamics

The screw compressor and screw expander 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 massflow control of compressors and expanders.

# 2 Fuel cells- working principle

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.



# Fig 1: Basic structure of a PEM fuel cell

In a fuell cell hydrogen and oxygen react in a controlled so called "cold burning" reaction. The basic layout of a PEM (Proton Exchange Membrane) fuel cell, the type mainly used in transportation applications, is shown in **Fig 1**.



Fuel cell reaction:  $H_2 + 1/2O_2 \rightarrow H_2O$ 

Fig 2: Chemical reactions in a PEM fuel cell [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:

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

Туре	Electrolyte	Working temperature [°C]	Remarks	Main uses
<b>AFC</b> (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
<b>PEMFC</b> (Proton Exchange Membrane Fuel Cell)	Proton conducting polymer	20-120	High power density, high flexibility, rugged	Automotive applications
SOFC (Solid Oxide Fuel Cell)	Solid Zirkonium Oxide	850-1000	Fuel tolerant, high efficiency	Power generation

Fig 2 gives an overview over the chemical reactions involved.

Table 1: Basic types of fuel cells

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.

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 layouts and load lines

To make a fuel cell work peripheral components have to be added, together forming the fuel cell drivetrain, consisting of the main subsystems:

- Fuel cell system
- Hydrogen supply
- · Air management system
- Electric power system and drive





Fig 3 shows a typical PEM fuel cell drivetrain with petrol reformer for onboard hydrogen generation, the most complex layout.

The air management subsystem consists of three main components:

- Air compresor supplying air to the fuel cell cathode (CAC)
- Air compressor supplying air to the fuel processing unit (FPUC)
- Expander for the fuel cell off-gas

The requirements for these main components vary considerably and will be discussed separately.

# Cathode air compressor (CAC)

The cell voltage developed by a fuel cell is significantly dependent on the cathode air pressure. **Fig 4** shows a typical set of curves for the cell voltage over the current drawn with the cathode air pressure as parameter. The advantage of running the fuel cell on pressurized air can be seen clearly.

This advantage has to be balanced against the increasing power required for the compressor when the pressure ratio rises.

Another reason to use higher working pressures is the humidity of the air required to obtain sufficient conductibility of the membranes. At higher pressures higher relative humidities are obtainable. In some cases the humidification of the air is achieved by water-injection immediately into the compressor, at the same time increasing the thermodynamic efficiency because of the internal cooling due to the evaporation of the water. The water used for the humidification is carried on board. To avoid the need to replenish water from external sources it is necessary to recuperate at least as much water from the off-gas stream as has been spent during the humidification process.



Fig 4: Typical pressure sensitivity of a PEM fuel cell stack

The mentioned influences result in a typical pressure curve for the cathode air compressor as a function of the fuel cell power shown in **Fig 5**.



Fig 5: Typical pressure curves over the fuel cell load.

# FPU air compressor (FPUC)

The FPU air compressor delivers air to the fuel processing unit (reformer) for the on board hydrogen generation. Assuming equal pressures of air and hydrogen at the fuel cell stack inlet the pressure necessary for the FPU is equal or higher than the pressure delivered by the cathode air compressor to make up for pressure losses in the FPU. The FPU compressor's mass flow is about one fifth of the cathode air compressor's.

A typical pressure curve for an FPUC can also be found in Fig 5.

#### Expander

As a significant amount of power is consumed during the compression process it is advisable to utilize an expander to recover exergy from the fuel cell's offgas to increase the overall efficiency.

The expander's maximum inlet pressure is slightly lower than the compressor's outlet pressure because of the mass flow dependent pressure drop in the fuel cell stack. The resulting curve for the expander inlet pressure is also shown in Fig 5.

Another important task for the expander is the recuperation of process water contained in the off-gas. As already mentioned water is needed for humidification of the membranes and in some processes in the FPU.

During the expansion steam contained in the off-gas condenses partially. The resulting liquid phase can be separated from the air stream and be reused in the system.

Another task that should be taken over by the expander is the backpressure control, replacing a conventional throttle. The backpressure is then regulated by controlling the mass flow through the expander, similar to control systems used in automotive superchargers.

It is generally accepted practice to couple the CAC and the expander onto a single shaft, forming an integrated compressor expander module.

## 4 Performance targets

Table 2 shows the main target values for fuel cell air management system components as defined by the guidelines of the US Department of Energy (DOE) [2]. The values shown are valid for machines intended to supply a 50 kW fuel cell stack.

Parameter	Compressor	Expander	Electric-motor	
Max. mass flows :				
Dry air [kg/h]	270	295		
Steam [kg/h]	0-11	31-55		
Inlet pressure [bar]	1.0	2.8		
Outlet pressure [bar]	3.2	1.0		
Nom. Inlet temperature [°C]	25	150		
Working temperature [°C]	-40 - 60	65 - 150	-40 - 60	
Efficiency at 100% flow	0,75	0,9		
Efficiency at 20% flow	0,65	0,8		
Max. Power [kW]	12.6	8.3	4.3 continuous, 6.0 peak	
Turndown ratio	10:1	10:1		
No. Of stages	1-2	1	1	
Package Volume [I]	4	(without heat exchangers)		
Weight [kg]	3 (with		exchangers)	
Production cost at 100.000 units/year	200 \$			
Startup time [s] <		5 s for 90 % of max. speed		
Dynamic response time [s]	< 4 s	< 4 s for 10-90 % of max. mass flow		
Noise emission [dB(A)]	< 80			

Table 2: Basic requirements for an air management system for 50 kW fuel cells [2]

In addition to the "hard" targets listed the components have to meet some less well definable requirements.

Fuel cells are highly susceptible to damage because of contaminated 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 byproducts in the components itself.

Under today's ambient conditions the suction air is heavily contaminated by gaseous compounds like sulfur, 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  $ha^{ve}$  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.

When moving parts touch abrasion occurs. Especially conductive abraded particles (ions) will harm the fuel cell and must be avoided.

Corrosion may become an issue when water is involved in the process because of water injection into the compressor or condensation in the expander.

As the water used is deionized it has a strong tendency to solve ions out of the materials it comes into contact with. Any materials that might potentially come into contact with water must be made of materials able to withstand this attack or be coated suitably, as otherwise the quality of the water will suffer the air may get contaminated by corrosion byproducts and the surfaces suffer.

As already mentioned it is desirable to use the expander to effectuate the pressure control within the air system by varying it's suction capacity. Especially when the expander is coupled to the compressor onto a single shaft this becomes a challenging task as the speed ratio between the machines is fixed and the expander speed can no longer be used to control the mass flow. It

will then be necessary to use advanced control mechanisms, e.g. inlet slide valves or internal bypasses to achieve acceptable dynamic behaviour.

The noise emission of the air management system is a point of very high importance, especially in the context of the otherwise almost noiseless fuel cell drivetrain. The noise levels have to be kept to the absolute minimum possible to meet the ever increasing expectations for the car occupants comfort.

Lower raw noise emission of the unit results in less noise isolation material needed, reducing cost, complexity, package size and weight.

The fuel cell itself is able to react almost instantaneously to changes of the load. The limiting factor for the dynamic of the whole system is the media supply (hydrogen and air), mainly limited by the inertia of the compressors and their electric motors.

To achieve satisfying dynamics acceleration times for the compressor significantly lower (0,5 – 1 s for 10-90 % mass flow) than the values listed in Table 2 are desirable.

#### 5 Future challenges

Once the basic technical challenges are met and the number of fuel cells produced increases production issues will become very important to be able to supply the necessary quantities at low cost.

This point has to be considered in the early design phases as not every technical solution is readily adaptable to the highly mechanized mass production techniques necessary once production increases to the amounts common in the automobile industry.

#### Literature

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