Development of an oil-free turbo compressor for mobile fuel-cell applications – challenges and results

The compressor for supplying air to a fuel-cell stack is a critical component in the balance of plant (BoP), especially for mobile applications. The main requirements of the compressor are the performance concerning pressure ratio, mass flow and efficiency, while having a minimal size and weight. The turbo compressor technology is ideally suited to meet these requirements. Air bearings are employed to meet the long lifetime requirement and the need of an oil- and particle-free air supply. The fuel-cell air supply requirements conflict with the turbo compressor's pressure ratio and mass flow characteristics. The possible solutions and their impact on the compressor design and fuel-cell operation are described in this article.

1 INTRODUCTION

Mobile fuel cells, such as in automotive applications, are usually powered by hydrogen from a hydrogen storage and compressed ambient air. Typical requirements for the air supply for fuel cells in mobile applications are high efficiency while offering sufficient lifetime and reliability to comply with automotive standards. The sensitivity of fuel cells towards impurities such as particles and oil besides others demand an oil free lubrication and contact free bearings. Especially in mobile applications, additional requirements are low weight and volume.

Centrifugal compressors, also called turbo compressors, achieve the performance level of conventional compressor technologies such as piston or scroll compressors with up to 50 times less volume and weight. Turbo compressors work continuously such as fuel cells, thus no pressure fluctuations or shock pressure occurs. The high speed of turbo compressors allow to miniaturize the aerodynamics and the motor, what results in high power density. Therefore, turbo compressors are ideally suited for mobile applications (Blunier & Miraoui, 2010). Air bearings are most beneficial to cover the requirements concerning lifetime and oil-free air supply (Casey, Krähenbühl, & Zwyssig, 2013) (Kolar, Zwyssig, & Round).

Compared to internal combustion engines utilizing turbo chargers, where a turbine stage drives a compressor stage fuel cells have too low exhaust enthalpy to meet the power requirement of the compressor stage by the turbine stage only, thus electrically assisted turbo chargers are required. For passenger cars, which are typically operated at low continuous load, a turbo charger with electric assistance is too complex, and can be simplified to a pure electric turbo compressor without turbine stage. Furthermore, by decoupling the air supply from the operation point of the fuel cell by a controllable backpressure valve, the control of the whole fuel cell system can be improved.

Fehler! Verweisquelle konnte nicht gefunden werden. shows the sectional view of an air bearing turbo compressor. The turbo compressor is based on several individual technologies such as the aerodynamic compressor stage, the electric motor and the bearing. The bearing technology (air, magnet or ball bearing) defines the achievable lifetime and influences the other design aspects significantly. The high power density achieved by miniaturising the size of the turbo compressor requires a careful thermal design. The system design approach considering the different interactions of the various design aspects finally enable an optimized design of a miniaturised turbo compressor.

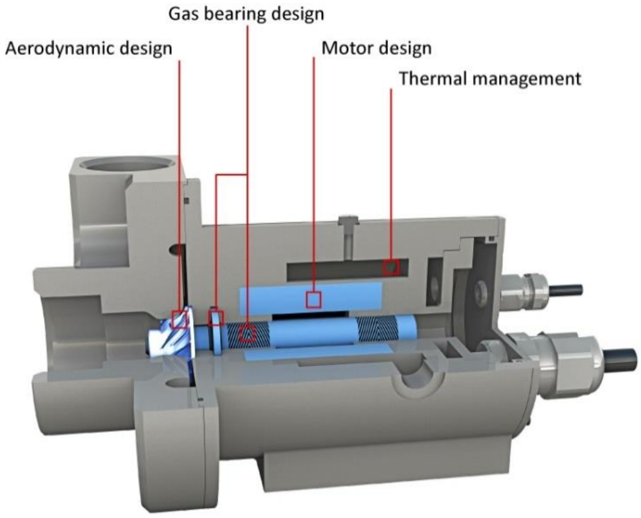

Fig. 1: Sectional view of an air bearing turbo compressor

2 Fuel cell air supply demand vs. compressor characteristics

2.1 How fuel cells operate

Fuel cells generate electrical energy by the reaction of hydrogen and oxygen into water. The oxygen is taken from the ambient air. The air mass flow provided by the compressor defines the fuel cells' output power. To force the air through the fuel cell, overpressure is required to overcome the pressure drop of the fuel cell. As of combustion engines, the fuel cells' energy density and efficiency can be increased by increasing the reaction pressure while maintaining the fuel cells' size. For mobile applications, a higher reaction pressure is commonly used (Jens, et al., 2016). These two boundary conditions defined by fuel cells lead to the requirement of a defined mass flow and absolute pressure at the fuel cells' inlet at a given demand of electrical power from the fuel cell.

2.1.1 Operation strategy of fuel cells

In traction applications, fuel cells are used as range extenders in quasi-stationary operation in combination with large batteries, or as full range fuel cell operated dynamically in combination with small batteries. The used operation strategy defines the dynamic behaviour required by the fuel cell and therefore by the compressor. Beside the strategy, fuel cells are controlled with or without a backpressure valve, leading to different characteristic operation requirements in mass flow vs. pressure as illustrated in Fig. 2. In range extender applications a constant operating point at optimized fuel cell system efficiency is commonly targeted without or with a fixed back pressure orifice (red curve). In full range fuel cell applications typically a variable back pressure is used to increase the fuel cell system efficiency over a wide range (green curve).

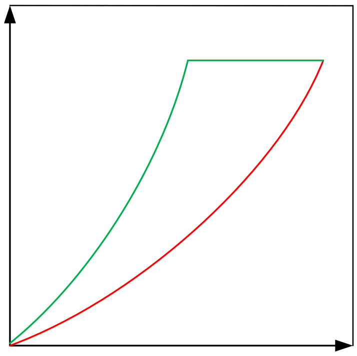

Fig. 2: Fuel cell control strategy with variable backpressure valve (green) vs. fixed backpressure orifice (red)

2.2 How turbo compressors operate

Turbo machines are flow machines with a defined pressure ratio Π and the defined mass flow $\dot{m}$ for a given rotational speed. The compressor map is used to describe the compressors characteristic: pressure ratio over mass flow Fig. 3. Technical limits such as aerodynamic and mechanical limits define the stable operating range of the compressor map. Surge, as a well-known aerodynamic instability, which is caused by flow separation, is indicated by the surge line. Blockage or choke occurs when the flow's speed reaches the speed of sound in any flow path and the maximum allowable speed of the compressor. Surge must be avoided and therefore the surge line represents the left border (low volume flow) of the compressor map while choke is the right border (high volume flow). The upper limit of the compressor map is defined by the speed limit, defined by the material strength or available compressor motor torque.

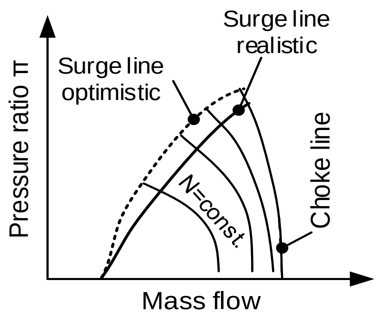

Fig. 3: Compressor map

The temperature and pressure dependency are exemplary illustrated in the following Fig. 4 to **Fehler! Verweisquelle konnte nicht gefunden werden.** for different inlet pressures, which occur e.g. in different altitude operation while **Fehler! Verweisquelle konnte nicht gefunden werden.** to Fig. 9 illustrate the impact of different inlet temperature, which can occur in any altitude. For comparison reasons the maximum compressor speed N_{max} (shown in the figures) is kept constant.

Fig. 4 and **Fehler! Verweisquelle konnte nicht gefunden werden.** show the compressor map with the pressure ratio over mass flow. Fig. 5 and Fig. 8 show the power map with the shaft power (power required from the aerodynamics, excluding motor and bearing losses) over mass flow. **Fehler! Verweisquelle konnte nicht gefunden werden.** and Fig. 9 show the compressor map with absolute pressure over mass flow.
The behaviour and links described in the following assume that only one parameter is changed and all others are kept constant. Increasing the inlet density by increasing the inlet pressure (Fig. 4) or decreasing the inlet

temperature (**Fehler! Verweisquelle konnte nicht gefunden werden.**), the mass flow increases for constant speed, resulting in increasing power demand (Fig. 5 and Fig. 8). With increasing temperature the pressure ratio decreases (**Fehler! Verweisquelle konnte nicht gefunden werden.**), resulting in decreasing power demand (Fig. 8). The absolute outlet pressure decreases with the inlet pressure while maintaining a constant pressure ratio (**Fehler! Verweisquelle konnte nicht gefunden werden.**).

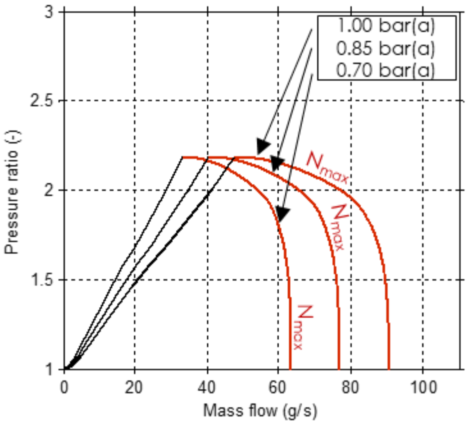

Fig. 4: Compressor map at constant inlet temperature (20°C)

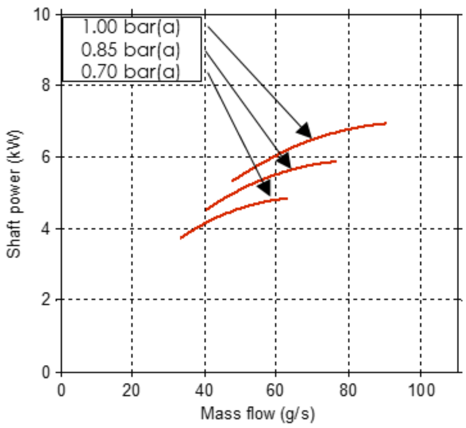

Fig. 5: Power map at constant inlet temperature (20°C)

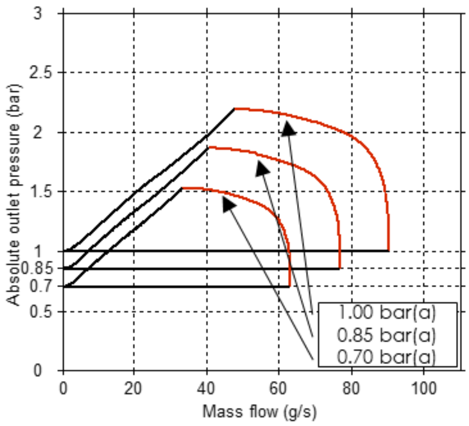

Fig. 6: Compressor map with absolute outlet pressure at constant inlet temperature (20°C)

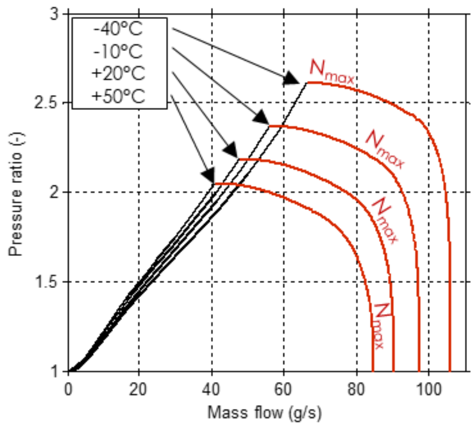

Fig. 7: Compressor map at constant inlet pressure (1 bar abs.)

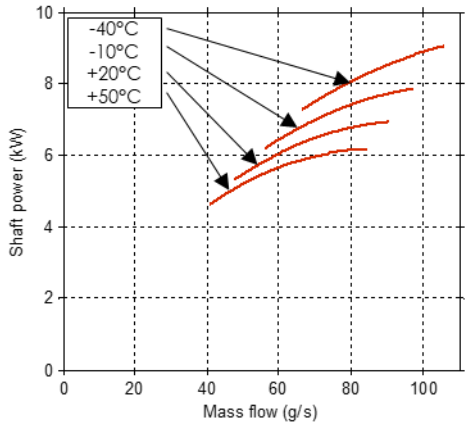

Fig. 8: Power map at constant inlet pressure (1 bar abs.)

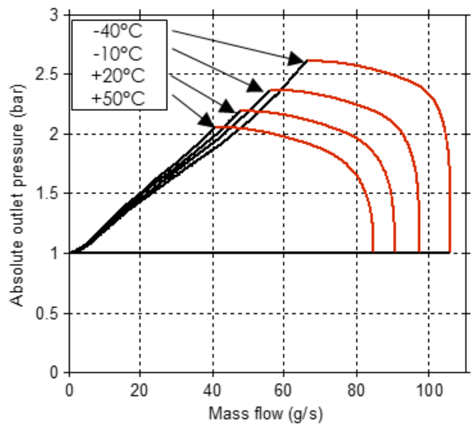

Fig. 9: Compressor map with absolute outlet pressure at constant inlet pressure (1 bar abs.)

2.3 Conflict in fuel cell air supply requirements vs. turbo compressor characteristics

This chapter summarizes the conflict introduced by the fuel cell operation principle in section 2.1.1 and the turbo compressors operation principles in section 2.2.

To accommodate the fuel cells' requirement at sea level and in high altitude, e.g. 1'000 m, the turbo compressor needs to have a certain margin to compensate the different inlet conditions. This oversizing is called high altitude margin, which commonly is coped by higher rotational speeds. For the following discussion the simplified assumption that the required mass flow is 110 g/s at a compressor outlet pressure of 2.0 bar abs. apply. The full fuel cell power at sea level is available when the compressor requirements of the first column "sea level" in Table 1 are provided with a compressor power of about 10.5 kW. Assuming the same fuel cell output power should be available for the entire range from sea level up to an altitude of 4'000 m, the compressor power range is up to 18 kW.

Altitude	Sea level	1'000 m	2'000 m	4'000 m
$p_{in}\ (bar\ abs.)$	1.013	0.891	0.784	0.606
$T_{in}\ (°C)$	20	20	0	-10
$PR\ (-)$	2.0	2.3	2.6	3.3
$p_{out}\ (bar\ abs.)$	2.0	2.0	2.0	2.0
$\dot{m}\ \left(\frac{g}{s}\right)$	110	110	110	110
$P_{in}\ (kW)$[1]	10.5	13.4	14.6	18

Table 1: Example for compressor power and pressure ratio range

3 Solutions and impact

To match the requirements of the fuel cell with the compressor performance in general two approaches can be chosen. Either the compressor is designed for the maximum demand of the fuel cell which corresponds to the lowest inlet pressure and highest inlet temperature or the fuel cell requirement is derated in certain operating conditions.

3.1 Oversizing the compressor

To meet the demand of the fuel cell in high altitude, a pressure ratio higher than the pressure ratio at sea level is required. If the compressor is designed to meet this worst case operating point (Table 1, column "4'000 m"), the power demand leads to an oversizing of the compressor. Consequently, the compressor is operated in part load for all inlet conditions except worst case as described in section 2.3.

3.2 Derating of the fuel cell

Derating refers to the fuel cell output power, which is lower than the rated power in certain conditions. In this case a compressor is chosen to meet the operating point which is defined as main or rated operating point. For

[1] Assumptions: Constant efficiencies $\eta_{com,isentropic} = 72\%, \eta_{motor} = 95\%, \eta_{converter} = 95\%$

Besides this, the turbo compressors' efficiency η, also depends on the inlet conditions and operating point.
The maximum efficiency reduces towards surge and choke.

higher load demand, e.g. for acceleration (short period with higher mass flow and pressure demand) or high altitude the compressor may be operated in overload outside the optimum operating conditions e.g. at low compressor efficiency, until a thermal limit is reached. At the same time, the provided compressor mass flow and outlet pressure is too low for the described case at “4’000 m” altitude in section 2.3 and the fuel cell system has to be derated in this operating point, meaning a reduced fuel cell net power.

3.3 Combination of oversizing and derating

The mass flow and pressure requirement needs to be coped at sea level and up to a certain altitude. According to section 2.2 the outlet pressure and mass flow decreases with decreasing inlet density, while maintaining the compressor speed and the inlet temperature. To increase the outlet pressure and mass flow a higher speed is required, the so called speed or high altitude margin. For higher altitudes, a reduced pressure is acceptable resulting in a fuel cell system derating, meaning a reduced fuel cell net power. A typical altitude up to which the mass flow and (compressor outlet) pressure must be maintained is 1’000 m. Such a combination of oversizing and derating is commonly targeted.

4 Summary and outlook

The requirements for the air supply for mobile fuel cell applications are introduced and compared to the characteristics provided by a turbo compressor, and the resulting conflict is highlighted. Different solutions to cope with this conflict are introduced. The interaction between design aspects and challenges in the design of turbo compressors are described.

5 References

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