

Air Compressors for Fuel Cell Vehicles: An Systematic Review

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ABSTRACT

Even though air compressors for traditional vehicles and fuel cell vehicles (FCVs) share many similarities, a fuel cell vehicle cannot directly employ the effective and mass-produced traditional vehicles' air compressors. This is because the fuel cell vehicles have special requirements, such as oil free, low flow rate with high pressure ratio, high efficiency, and low weight and volume.

In order to find suitable air compressors to match the fuel cell system (FCS)'s requirements, different air compressors' performance and physical characteristics are compared. These air compressors include screw compressor with expander, roots compressor with expander, turbocompressor, and scroll compressor with expander. The comparison and analysis is both theoretical and practical.

Results show that the turbocompressor and the roots compressor/expander have higher performance compared to the others in the aspects of input power, system efficiency, weight, and volume. However, the two of them also show some defects. The turbocompressor has a limited turndown ratio due to the surge. And the roots compressor has a limited pressure ratio and pulsation characteristics.

The application of air compressors in FCVs is also studied. Literature review indicates that the turbocompressor is most popular among all FCVs. All the findings in this research will contribute to the selection and design of the air compressors for FCVs, which are on the edge of mass production.

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INTRODUCTION

Hyundai released the world's first series production FCV in 2013. Toyota also announced the sales launch of Fuel Cell sedan in Japan before April 2015. All these news indicate that FCVs are on the edge of mass production. For several decades, automotive manufacturers are trying to looking for an alternative to fossil fuel to reduce the CO₂ emissions, hydrogen will be our most sustainable option. Not only because hydrogen can be produced from renewables like solar and wind but also because the only emission from the tailpipe is water vapor. As shown in figure 1, compare to gasoline internal combustion engine vehicle (ICEV), diesel ICEV and plug-in electrical vehicles, FCVs have lowest hypothetical low carbon emissions, and zero greenhouse gas (GHG) emissions in the vehicle operations cycle, the GHG emissions come from the well-to-pump cycle (fuel production), but this scenario will get improved as hydrogen production technologies improve.

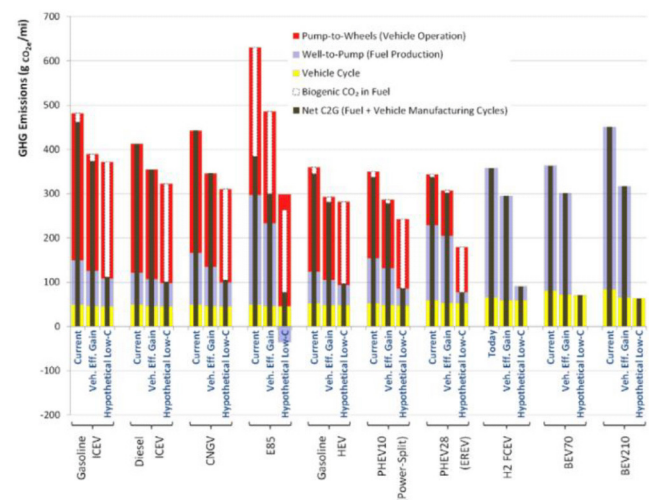


Figure 1. Contributions of vehicle cycle, fuel production and vehicle operations to C2G GHG emissions [1]

AIR SUPPLY SYSTEM

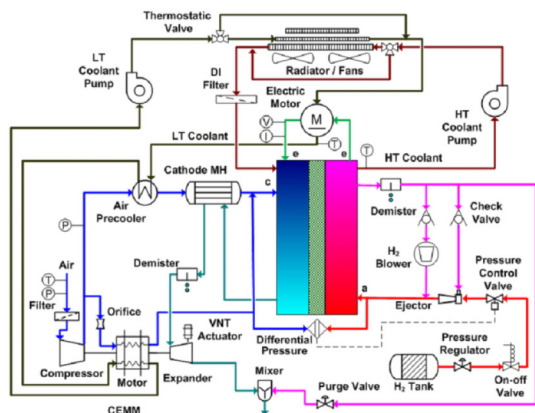


Figure 2. Fuel cell system and air supply system [2]

Air supply system, consisting of air filter, air compressor, optional expander, electrical motor, controller, air cooler, and cathode humidifier as show in figure 2, provides the continuous air flow which allows the stack to properly react on the cathode to recombine oxygen with the hydrogen's protons and electrons resulting in water and heat. FCS power output directly depends on the air mass flow, air mass flow, in turn, is a function of pressure and volume flow. The pressure is a significant parameter that has great influence on the FCS performance (power density, system efficiency, water balance, heat loads), stack weight, size, and cost, which deserves special attention. Pressurization from slightly above atmospheric pressure up to 2-4 bar can significantly improve the power density and water balance, and reduce heat rejection, there also other benefits. This pressure level is similar to boosted internal combustion engines (ICE), the air mass

flow is of similar magnitude as boosted ICE as well. However, the existing air compressor components of boosted ICE cannot be indirectly applied to FCS due to following reasons [4].

- Air cleaning, air supplied to FCS can't contain particles, chemical substance, etc., which needs oil-free air compressor components transport air to fuel cell stack, and limit the application of oil lubricated air compressor components.
- High efficiency. Unlike the boosted ICE, FCS provides the bulk of power to drive the air compression system because of low exhaust gas temperature.
- Low weight, volume and cost. Industrialization of fuel cell vehicles is restricted by power density and cost, so fuel cell vehicles have more stringent requirements on weight, volume and cost.
- Good NVH behavior. Air supply system is the biggest NVH source in FCS, improving the NVH conditions in FCS will meet more challenges than in boosted ICE.

In order to overcome these gaps, institutions, universities and vehicle manufactories spend plenty of money and energy to develop a variety of air compressor components.

Through comparing the similarities and differences with air supply compressor system, this paper analyzes the special requirements of FCS air compressor system. Based on these requirements, performance and physical characteristics of kinds of air compressors are compared from theoretical point. Several type air compressors for fuel cell vehicle (FCV) application are introduced and compared, the results could be used to compare with theory analysis, and find out the appropriate air compressors for FCV application.

Table 1. Survey of different charging systems [3]

	Compressor/Expander		Compressors							
	Turbo-charger	electric Turbo	Roots,2-lobe	Roots,3-lobe	Screw	Scroll	Rotary Piston	Vane	Piston	Centrifugal
Size	0	-	-	-/-	0/-	-	-	-	-	+
Weight	0	0/-	-	-/-	-	-	-	-	-	0
Rotational Inertia			High	High	Middle	Low				low
Vibrations	0	0	0	0	0	-	0	-	-	0
Internal Compression Ratio			No	No	Yes	(Yes)	(Yes)	(Yes)	(Yes) ¹	
Temperature Rise	0	0	-	-	+	0/+	0/+	0	0	0
Back Pressure	Yes	Yes	No	No	No	No	No	No	No	No
Drive Power Requirement	No	+	-	-	-	0	0/-	-	0/-	
Noise, Pressure Fluctuations	0	0/-	-	-	-	-	-	-	-	0
Pressure Ratio ²	3.0-3.5	3.0-3.5	2.0	2.0	3.0	2.2	2.0	2.0	2.0	3.0-4.0

++ good suitability
+ suitable
0 suitable with restrictions
- not advisable
-- unsuitable

¹ possible with valve timing
² available for passenger cars

THEORETICAL SURVEY OF DIFFERENT AIR COMPRESSION SYSTEM

Generally, air compressors are divided into the following two different categories based upon the operation principle [4].

- Positive displacement compressors
- Aerodynamic compressors

The turbo compressors belong to the aerodynamic compressors while all supercharger (or mechanical chargers) belongs to the positive displacement compressors. The significant criteria for choosing a suitable compression system for FCV application are listed and compared in table 1. According to special requirements for FCV application, turbocompressor, electrical turbocompressor and centrifugal compressor have obvious advantages in size, weight, pressure ratio, noise and pressure fluctuations, with expander, turbocompressor and electrical turbocompressor can reduce power requirements than centrifugal compressor. On the other hand, scroll compressor, screw compressor and rotary piston have better performance in temperature rise (efficiency). The following sections will describe relevant air compressor/expander (optional) in detail.

SCROLL COMPRESSOR/EXPANDER

Scroll compressor belongs to positive displacement compressors, which is widely option for air condition compressor system in automotive market. Scroll compressor can supply air mass flow and tune pressure ratio continuously without oil lubrication, the operating efficiency of a scroll compressor exceeds the traditional piston compressor particularly under low mass flow condition. The volumetric efficiency of a typical piston compressor is 65%, however scroll counterpart can typically achieve 85% efficiency [5]. Due to these aspects, scroll compressor has been chosen as air compressor for FCV application by some companies, such as Toyota, UTC Power, etc.

Arthur D. Little, Inc has developed a scroll compressor/expander module (CEM) for pressurization of 50 kW automotive FCS [6] [7]. Larger displacement and higher speed are employed in order to achieve 76 g/s flow, suitable for a 50 kW fuel cell, magnesium alloy scrolls are used to reduce weight and reduce bearing loads. With these design, scroll CEM gains excellent efficiency and shaft power benefits as shown in figure 4, 5. But the developed scroll CEM has fatal defects in volume and weight, 27 liters and 36 kg (not including motor), that is too large and heavy for application in FCV application.

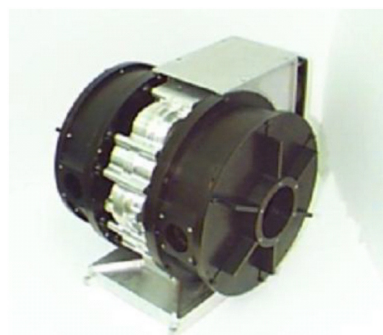


Figure 3. Scroll compressor-expander module [6].

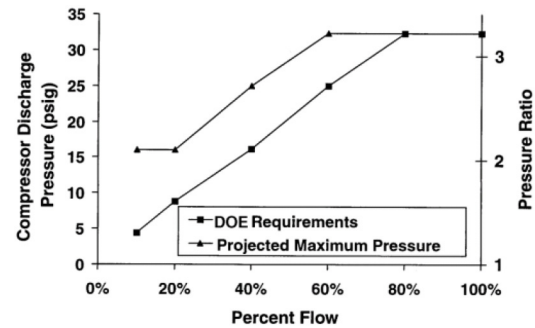


Figure 4. Scroll CEM operation envelope [6].

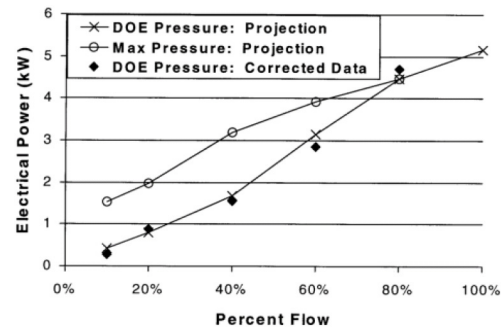


Figure 5. Scroll CEM shaft power [6].

VARIABLE DELIVERY COMPRESSOR/EXPANDER

Piston compressors have merit in the area of low power consumption across the operation range, especially at the dominant (20%~30%) operation level, and of variable flow control independent of pressure, which mean Piston compressor can achieve high turndown ratio. Also, energy recovery from the power system exhaust gases and system pressure are simplified and more flexible in the piston approach.

VAIREX corporation has used its dry cylinder compressor technology to develop an integrated air system (the expander is an integrated part of the total system) for installation in 50 kW fuel cell demonstrator system (figure 6) [8] [9].

Variable delivery compressor/expander shows attractive power consumption performance versus pressure ratio and air mass flow. The net shaft power to drive the air compressor system is only 5.4 kW at 76 g/s mass flow and 3.2 bar discharge pressure. However, this value is based on a 250° C flow inlet temperature to the expander, while common exhaust gas temperature of FCS is about 80° C, in this case the VAIREX developed variable delivery compressor/expander will consume more power from FCS. Variable delivery compressor/expander also has fatal defects in volume and weight (48-65 liters and 27 kg) as scroll compressor/expander, which directly limit the application in FCV.