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REVIEW ARTICLE

Air and hydrogen supply systems and equipment for PEM fuel cells: a review

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Summary
Air and hydrogen supply systems are key subsystems of polymer electrolyte membrane (PEM) fuel cell systems. This paper reviews the research on the gas (air and hydrogen) supply systems and equipment for PEM fuel cells. The scroll, screw, Roots, and centrifugal compressors are the major structures of compressors applied in the PEM fuel cells. Most studies and applications focus on air supply systems with centrifugal compressors. Four configurations of hydrogen supply systems are introduced, and characteristics of ejectors and hydrogen compressors are presented. The main technical developing directions for gas supply systems have been represented. The essential techniques involve the coupling of air compressors with PEM fuel cell systems, compressor and expander matching in the air supply system, integration of cooling and humidification in compressors, and energy utilization of high-pressure hydrogen gas.

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1. Introduction

For the past decade, energy and environmental issues have strongly attracted the attention of researchers. Many sustainable energy sources and technologies have been proposed, researched, and developed. As a highly efficient and clean energy device, the polymer electrolyte membrane (PEM) fuel cell has been studied in the past decade, which can be applied in transportation, distributed/stationary, and portable power generations (Wang, Diaz, Chen, Wang, Adroher, 2020). The PEM fuel cell becomes one of the desired power generation options in the 21st century (Wu 2016).

A PEM fuel cell system is mainly composed of the fuel cell, air supply system, hydrogen supply system, water and heat management system, and control system. Figure 1 shows the basic principle and the components of a PEM fuel cell system.

The core component of the PEM fuel cell system is the fuel cell, which is composed of a PEM sandwiched between the anode and cathode electrodes. Wang et al. review the materials and manufacturing of electrodes and membrane (Wang, Diaz, Chen, Wang, Adroher, 2020). Transport characteristics of PEM fuel cell stacks are summarized (Wu 2016), which include the transport characteristics in the membrane, catalyst layers, gas diffusion layers, and flow fields. And some researchers reviewed the technology and applications (Yun Wang et al. 2011), liquid water visualization (Bazylak 2009), and control system (Daud et al. 2017) of PEM fuel cells.

However, few publications focus on the gas (air and hydrogen) supply systems for PEM fuel cells. The parameters (pressure, temperature, mass flow rate, and recirculation ratio) of gas supply systems have a significant effect on the performance of PEM fuel cells. There is optimum operating pressure for the net power and system efficiency of PEM fuel cell systems. A rise in temperature leads to an increase in the water vapor transfer rate, but which results in a decrease in the water recovery ratio. Also, the energy consumption of these systems has a deep impact on the efficiency of PEM fuel cells.

This study aims to make a comprehensive review of gas supply systems for PEM fuel cells in recent years. Some technique trends for gas supply systems are represented.

2. Air Supply System

As a fuel cell using the electrochemical reaction between oxygen and hydrogen, oxygen can be easily obtained from the atmosphere. Hence, the air supply system is applied to many PEM fuel cells. The air supply system is an essential subsystem in PEM fuel cell systems (Zhiyang Liu et al. 2018). The main functions of the air supply system are as follows (Blunier and Miraoui 2010):

(1) ***Air cleaning***. Any particle (solid or oil) or chemical substance is harmful to the catalyst and the membrane. Air has to be cleaned by filters before flowing into the fuel cell stack.
(2) ***Air transportation***. The air supply system has to provide sufficient reactant (oxygen) to the fuel cell stack. The mass flow rate of the air supply system has a great influence on the oxygen concentration in fuel cell stacks (Bang et al. 2008)(Guo et al. 2019)(Corbo, Migliardini, and Veneri 2008)(Ji, Myung, and Kim 2011), which can be calculated by Equation (1) (Dicks and David 2018).

$$Q_{m,T} = 3.58 \times 10^{-4} \times \lambda \times \frac{P_e}{V_c} kg/s \quad (1)$$

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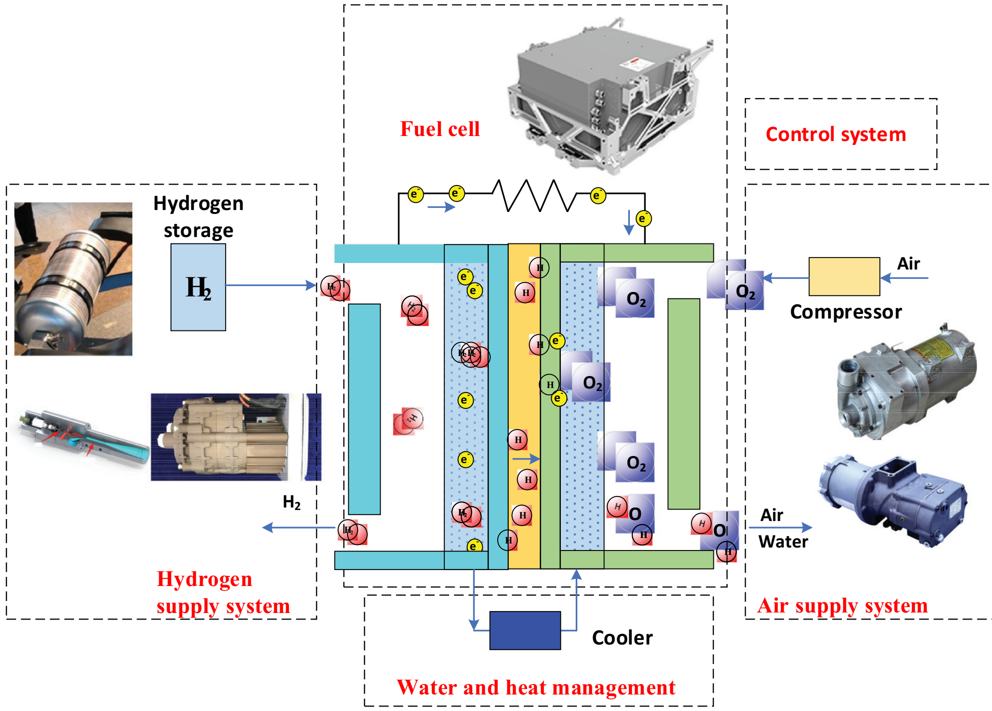


Figure 1. Schematic of PEM fuel cell system.

where λ is the air stoichiometry, the value is usually about 2.0; P_e is the power of the PEM fuel cell system (kW); V_c is the average cell voltage, and the value of it is 0.65 V.

(1) ***Pressurization***. In any case, the air is given under pressure above atmospheric pressure because of the flow loss in fuel cell stacks. And the air pressure has a significant effect on the performance of PEM fuel cells (Kim et al. 2005)(Akroot, Ekici, and Murat 2019). The optimal pressure takes around 1.5–2.5 bar.

(2) ***Humidification***. The polymer membrane has to be maintained in a fully hydrated state to obtain optimal performance. In some systems, air is humidified before flowing into the fuel cell stack. And the air supply system has to balance the water consumption.

The air filter, compressor, and humidifier are usually applied in a typical air supply system to realize the above functions. The research directions of the air supply system focus on the power consumption, compressor efficiency, air cooling, and humidification method.

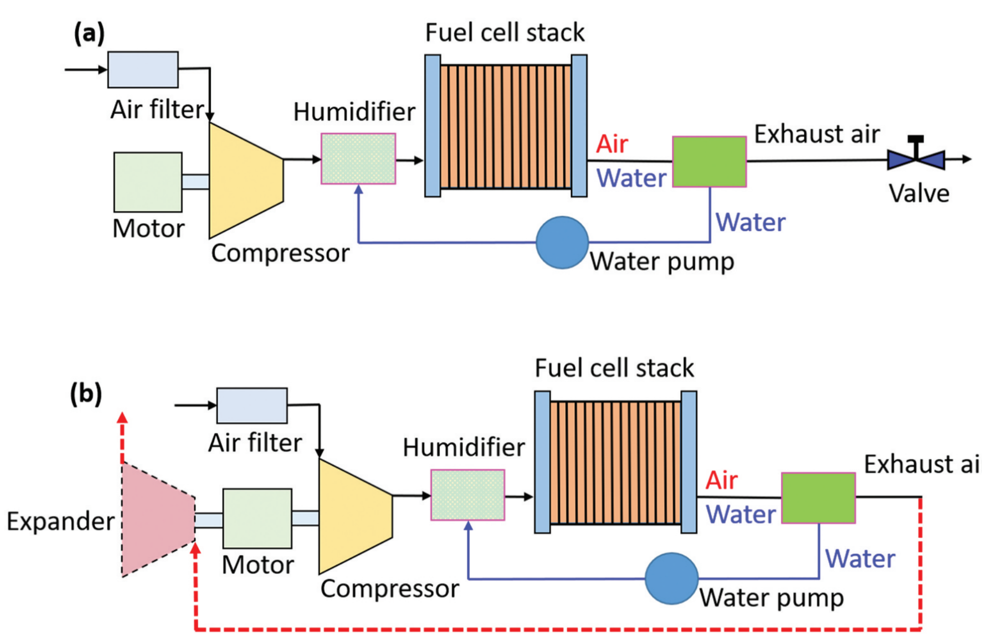


Figure 2. Schematic of air supply system (Blunier and Miraoui 2010): (a) Without expander; (b) With expander.

The power consumption of the air supply system (by compressors) is over 20% of the gross power of the fuel cell stack (Blunier and Miraoui 2010). Because the pressure of exhaust air from fuel cell stacks is over the atmospheric pressure, expanders can be used to recover the energy of exhaust air, and the usage of an expander can improve the net power capability by 14% (Blunier and Miraoui 2010). Figure 2 shows the schematic of the air supply system for PEM fuel cells. The schematic of the air supply system without an expander is shown in Figure 2(a). Figure 2(b) shows the layout with an expander. And the technical difficulty and equipment complexity increase when expanders are used in air supply systems. Hence, up to now, the air supply system without expanders (shown in Figure 2(a)) is used in most PEM fuel cells.

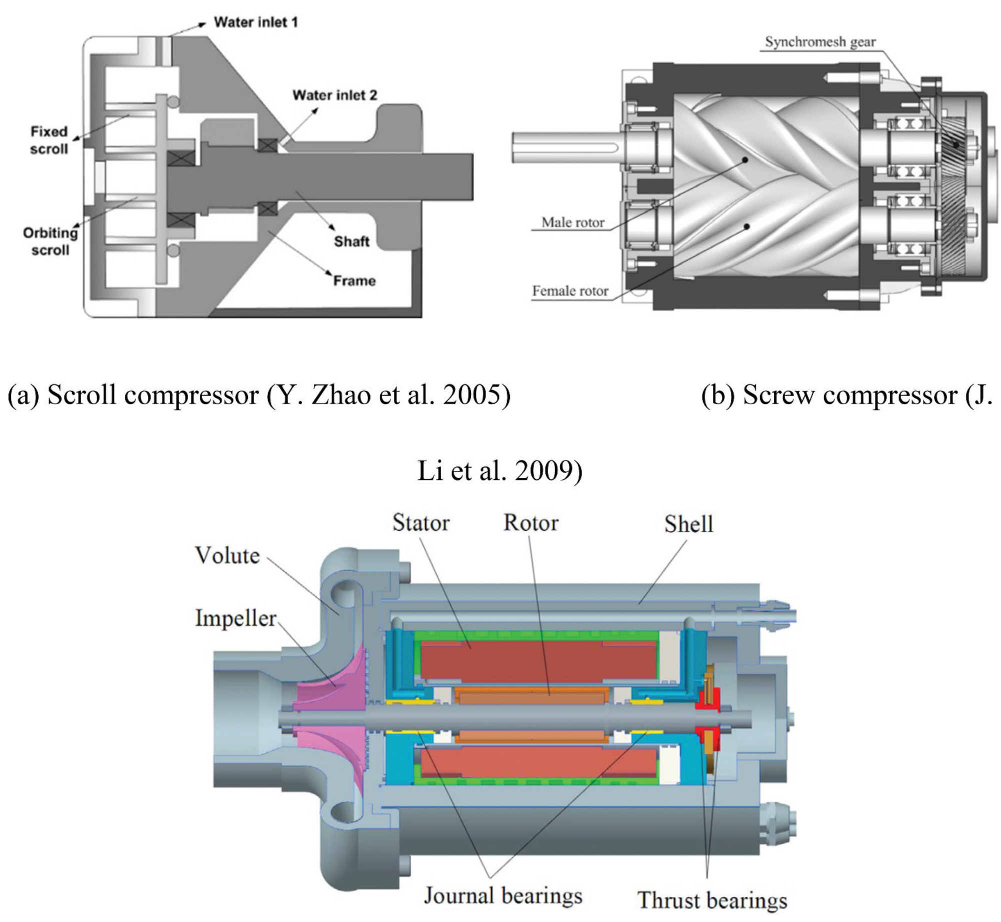
2.1. Air compressor

In air supply systems, compressors are key devices that significantly affect the characteristics of the air supply system and PEM fuel cells. Based on their working principles, two kinds of compressors can be used in the PEM fuel cells, i.e., positive displacement compressors and dynamic compressors. For positive displacement compressors, scroll, screw, and Roots compressors were investigated for PEM fuel cell systems. And for dynamic compressors, centrifugal compressors were studied and applied in PEM fuel cells. Considering the operating environment of PEM fuel cells, the compressed air should be oil free, so the oil-free compressors are the best choice for PEM fuel cells. Figure 3 shows the major structures of three types of oil-free compressors for PEM fuel cells. Table 1 shows the main parameters of compressors for PEM fuel cells reported by the references in recent years. It can be seen that most of the studies and applications focus on dynamic compressors (centrifugal compressors) in recent years.

2.1.1. Positive displacement compressors

The water injected scroll compressor was researched for a 30 kW PEM fuel cell with 5,000 rpm (Yuanyang Zhao et al. 2003)(Y. Zhao et al. 2005)(Yuanyang, Liansheng, and Pengcheng 2006). For scroll compressors applied in PEM fuel cells, the large value of the mass flow rate is a challenge, even though the pressure ratio and discharge pressure can satisfy PEM fuel cell systems (Qingqing Zhang et al. 2018b).

The oil-free and water-injected screw compressor was researched to be used in a 50 kW PEM fuel cell system (J. Li et al. 2009)(Y. He et al. 2018). The isentropic efficiency of the prototype compressor developed is 55%, with a discharge pressure of 2 bar and a speed of 9,000 rpm.



(a) Scroll compressor (Y. Zhao et al. 2005) (b) Screw compressor (J. Li et al. 2009)

(c) Centrifugal compressor (Ren and Feng 2017)

Figure 3. Basic structure of oil-free compressors for PEM fuel cells: (a) Scroll compressor (Y. Zhao et al. 2005) (b) Screw compressor (J. Li et al. 2009) (c) Centrifugal compressor (Ren 2017).

Table 1. Compressor research summary for PEM fuel cells.

Reference	Compressor Type	Flow rate	Pressure /bar	Rotation speed /rpm	remarks
(Yuanyang Zhao et al. 2003)	Scroll	1.56 m^3/min[a]	3.5	5,000	Water inject
(Y. Zhao et al. 2005) (Yuanyang, Liansheng, and Pengcheng 2006)	Scroll	95 g/s	3.0	5,000	Water inject
(Qingqing Zhang et al. 2018b)	Scroll	/	4.0	6,000	
(J. Li et al. 2009)	Screw	3.0 m^3/min	2.8	5,000	Water inject
(Y. He et al. 2018)	Screw	3.5 m^3/min	2.0	9,000	
(Ous, Mujic, and Stosic 2012)	Screw	94 g/s	5.0	3,000	Water inject
(Wan, Guan, and Sichuan 2017)	Centrifugal	80 g/s	2.2	100,000	
(Jiang, Khan, and Dougal 2006)	Centrifugal	300 g/s	2.2	50,000	
(Zhixiang Liu et al. 2016)	Centrifugal	150 g/s	2.43	201,500	
(Koyyalamudi and Nagpurwala 2016)	Centrifugal	2 kg/s	4.0	30,000	
(Thirumalai and White 2000)	Centrifugal	12.83 m^3/min	3.0	5,000	
(Zhang, Sichuan, and Wan 2020)	Centrifugal	100 g/s	3.0	100,000	

[a]1 m^3/min ≈ 21.5 g/s

Based on the working principle of positive displacement compressors, air pressure can be increased up to 2 bar easily by screw and scroll compressors, and the liquid can be injected into the working chamber of compressors to increase the efficiency by reducing the leakage and discharge temperature at the same time. Hence, the humidification process can be integrated into compressors by injecting water into compressors. But the rotation speed of screw and scroll compressors cannot be extremely high (usually lower than 10,000 rpm), which leads to the large volume and weight. Hence, they are not suitable for mobile devices very well, especially for automobiles.

2.1.2. Dynamic (centrifugal) compressors

As a dynamic compressor, the centrifugal compressor is probably more suitable for PEM fuel cells than positive displacement compressors because it has the characteristics of high speed (corresponding to the smaller volume and lighter weight), low noise, high efficiency, and high reliability. So, many researchers have studied centrifugal compressors for PEM fuel cells in different aspects.

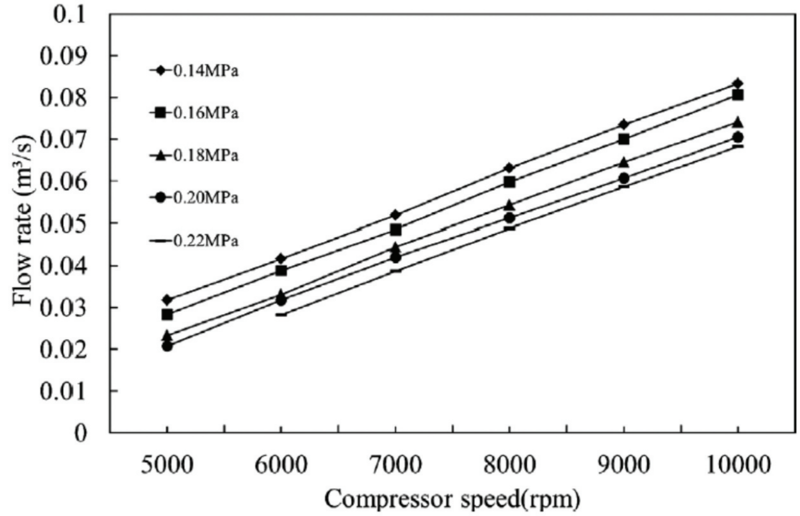
The performance of centrifugal compressors is influenced by the parameters of rotation speed and pressure ratio. The efficiency of centrifugal compressors changes hugely under different working conditions. There are stable and unstable working conditions for centrifugal compressors. And typical unstable conditions of centrifugal compressors are the stall, surge, and choked conditions.

Many investigators focus on the operating performance of centrifugal compressors in PEM fuel cell systems. Qin et al. (Qin et al. 2017) researched the operating pressure effect on the performance of a 20 kW PEM fuel cell system based on the experimental performance of an air centrifugal compressor. The results show that the optimum system operating pressure is about 1.2 atm. Empirical models (Wan, Guan, and Sichuan 2017)(X. Fang et al. 2014) are usually used by considering the experimental data. Including many kinds of losses, the dynamic model of a centrifugal compressor in the virtual tested computational environment was presented (Jiang, Khan, and Dougal 2006). It can be applied to any centrifugal compressor and fuel cell systems. A semi-mechanical and semi-imperial air supply system model based on centrifugal air compressors was established for a 150 kW PEM fuel cell engine (Zhiyang Liu et al. 2018)(Zhixiang Liu et al. 2016). Experimental and simulation results show that the control accuracy and celerity of the air compressor are well.

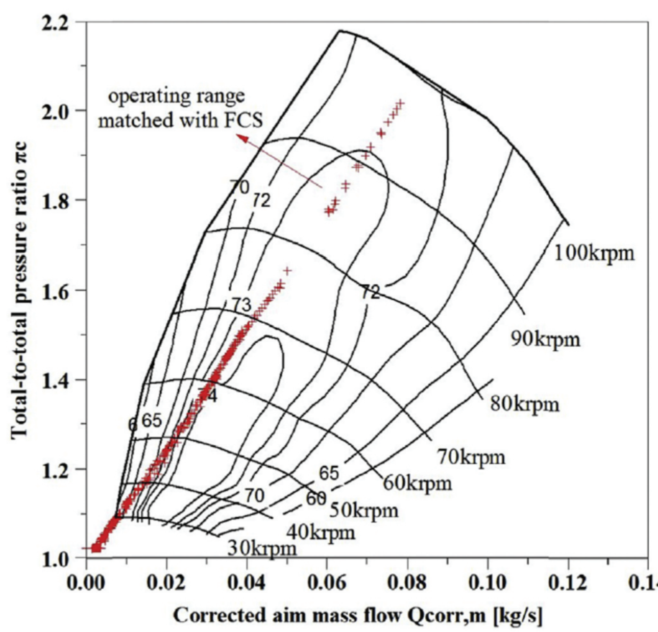
Surge and stall are two intrinsic characteristics of centrifugal compressors (Koyyalamudi and Nagpurwala 2016)(Han, IM, and YU 2016). To guarantee the safety of centrifugal compressors, they cannot be operated under surge conditions. Godard et al. (Godard, Trebinjac, and Roumeas 2018) tested the surge characterization of a centrifugal compressor for fuel cell, and the compressor surges abruptly with no pre-stall activity at a high rotation speed. An agglomerate model is introduced, and a model of the fuel cell system with a dynamic compressor is implemented. The results indicate that the oxygen concentration is most strongly affected by the surge of compressors (Han, Hwang, and Sangseok 2019). Laghrouche et al. (Laghrouche et al. 2013) proposed a load governor based on constrained extremum seeking PEM fuel cell oxygen starvation and compressor surge protection, and the scheme was verified by experiment. A fuzzy logic control solution was proposed for the compressor group supplying an embedded 5 kW PEM fuel cell system. The steady-state operation of a compressor for a PEM fuel cell system was studied by two operating models (Thirumalai and White 2000). It is found that the system efficiency is higher when the system is operated at a constant oxygen gas stoichiometry by varying the compressor speed. Ha et al. (Kyoung-Ku et al. 2013) studied the aero-acoustic characteristics of a centrifugal compressor for fuel cells. The broadband noise component due to the turbulent flow in the compressor increases during low flow rate conditions.

Some studies focus on the design, performance optimization, high-speed motor (Raminosoa et al. 2010), and new bearings of centrifugal compressors for PEM fuel cells. Wan et al. (Wan, Guan, and Sichuan 2017) researched the improved empirical parameters design method for centrifugal compressors in PEM fuel cell vehicle applications. The water-lubricated bearing for high-speed centrifugal compressors was studied by Ren et al. (Ren 2017)(Ren and Feng 2016). The performance of centrifugal compressors for a fuel cell was improved using aerodynamic optimization and data mining methods (Zhang, Sichuan, and Wan 2020).

Figure 4 shows the typical performance of positive displacement and centrifugal compressors. For a positive displacement compressor (Figure 4 (a)), the relationship between the flow rate and rotation speed is approximately linear. The pressure has not a directed relationship with the rotation speed, which means the highest pressure can be obtained under most rotation speed. And the change of isentropic efficiency is small under variable operating conditions. In the centrifugal



(a) Positive displacement compressor (Y. He et al. 2018)



(b) Centrifugal compressor (Wan, Guan, and Xu 2017)

Figure 4. Typical performance of positive displacement and centrifugal compressors: (a) Positive displacement compressor (Y. He et al. 2018) (b) Centrifugal compressor (Wan, Guan, and Sichuan 2017).

compressor (Figure 4 (b)), the relationships among pressure, flow rate, and rotation speed are more complicated. In general, the higher rotation speed leads to a higher flow rate and higher pressure. The isentropic efficiency of the centrifugal compressor changes dramatically under different working conditions.

Table 2 shows the features of various compressors. For scroll and screw compressors, the rotation speed can not be very high, which leads to the large volume and weight. But their operating range and stability are wide. For centrifugal

Table 2. Features of different compressors(Hou et al. 2020).

Features	Scroll compressor	Screw compressor	Centrifugal compressor
Rotation speed	low	medium	very high
Mass flow rate	low	medium	very high
Pressure ratio	high	high	medium/ high
Volume and weight	large	medium	small
Operation range	wide	wide	narrow
Stability	strong	strong	weak

compressors, the rotation speed can be very high. Hence, their volume and weight are small, which means they are suitable for mobile devices. But the control of centrifugal compressors should be careful because the stability of them is weak.

2.2. Expander

As shown in Figure 2, expanders can recover some energy from the exhaust gas to increase the efficiency of PEM fuel cells.

Up to now, studies of expanders are much less than that on compressors in PEM fuel cells. The reason may be that the configuration and operation of this system would become more complex if an expander is added. The exergoeconomic analysis of PEM fuel cell systems with an expander is made, and results show that the fuel cell system with an expander is more cost-effective than that without an expander (Sayadi, Tsatsaronis, and Duelk 2014).

The scroll expander was investigated for PEM fuel cells, and it is pointed out that the matching of operating parameters between the compressor and expander is essential for the practical application of the air supply system with an expander (Xiaojun et al. 2004). The screw expander was researched by the experimental method (C. Wang et al. 2020a) (Wang, C., Z. Xing, S. Sun, and H. Zhilong. 2020b2020). The power losses of screw expanders are analyzed, and the operating state of expanders is judged by the expansion-end pressure in the equivalent polytropic process. Match the mass flow rate of the expander with that of the compressor is a significant factor influencing the performance of the fuel cell stacks (C. Wang et al. 2020a). Figure 5 shows the schematic and recovered the power of the screw compressor-expander unit under different working conditions. The results show that the recovered power is even negative when the parameters match is not very well.

2.3. Humidification

Humidification is a critical issue for PEM fuel cells because the PEM needs to stay in a hydrated state to have high ion conductivity and durability, which requires proper humidification (Wilberforce et al. 2019)(Jiquan Han et al. 2021). There are many kinds of methods to make sure the humidification of the PEM (Bazylak 2009). These methods can be classified as internal and external methods. The physical methods and chemical methods are called internal humidification methods. The external humidification methods include the gas bubbling humidification, direct water injection(Jung et al. 2007), enthalpy wheel humidification(Casalegno et al. 2011), membrane humidifiers(Yan et al. 2020)(Baharlou Houreh et al. 2020)(Kord Firouzjaei, Rahgoshay, and Khorshidian 2020), and exhaust gas recirculation(Qinguo Zhang, Tong, and Tong 2020)(Shao et al. 2020)(X. Zhao et al. 2018). In addition, As mentioned previously, water injection methods can be combined with the working process of compressors. For the air supply system with positive displacement compressors, water can be injected into the working chamber of compressors directly. This approach has three advantages:

(1) Decrease the power consumption of compressors.
(2) Decrease the temperature of compressed air.
(3) Integrate the function of humidification into the process of compressors, which means the humidifier is no longer needed individually when the parameters of water injection into compressors are reasonable.

Centrifugal compressors applied for PEM fuel cells are all water-free in the literature of PEM fuel cells. But the water injection method has already been applied for centrifugal compressors in other fields (H. Yin et al. 2020). Hence, water-injected centrifugal compressors for PEM fuel cells may be developed by considering the materials, structure, and water injection control. Using water injection in centrifugal compressors also has the advantages mentioned above.

Figure 6 shows the layout of air supply systems with water injection to compressors. When the water injection layout is applied, air humidification is finished in the chamber of compressors, and the humidifier is no longer needed for the system. Because the pressure of exhaust air is higher than the pressure at the inlet of compressors, the control valve can replace the water pump.

2.4. Control techniques

Control targets of air supply systems are to supply the pure air with the appropriate mass flow rate and pressure to fuel cell stacks and to guarantee the safety of compressors at the same time. Control methods of air supply systems with centrifugal compressors are important to the operation of PEM fuel cells

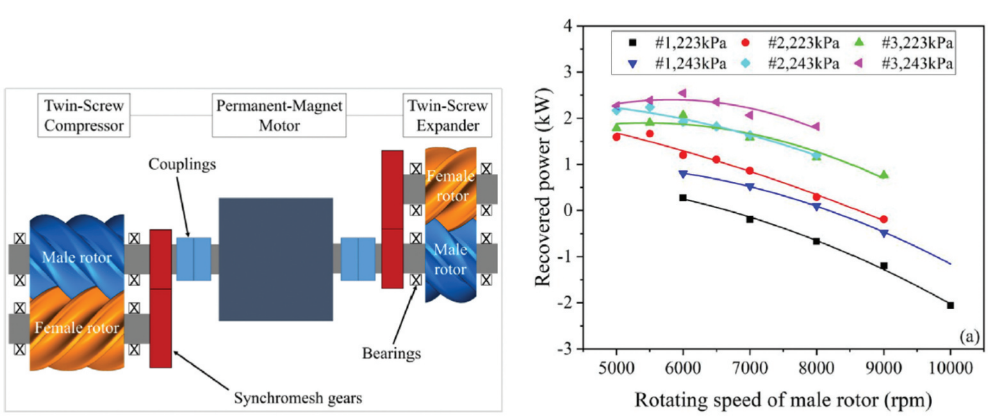


Figure 5. Schematic diagram and performance of screw compressor-expander unit (C. Wang et al. 2020a).

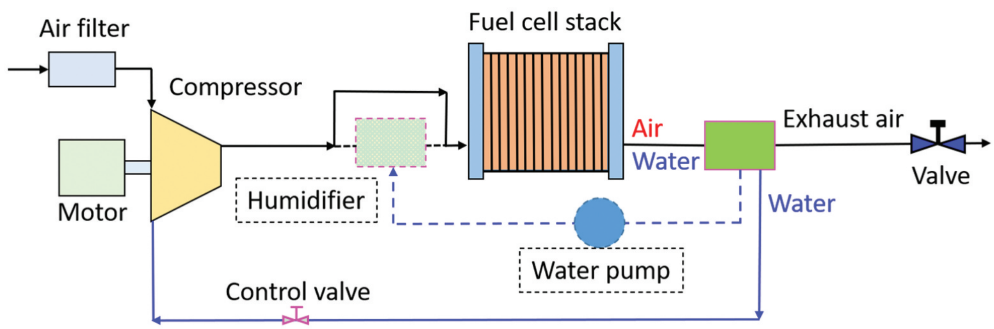


Figure 6. Air supply system with water injection for compressors (Blunier and Miraoui 2010).

because centrifugal compressors have a strong coupling between the mass flow and pressure (as shown in Figure 4) and exist unstable working conditions. Hence, most of the studies focus on the control of the air supply system with centrifugal compressors.

A reduced-order robust control is presented to keep a desired oxygen excess ratio for fuel cells (Hernández-Torres, Riu, and Sename 2017). A robust composite adaptive neural network controller using a high-gain observer is proposed to achieve a stable oxygen excess ratio control for the air supply system (Yunlong Wang, Wang, and Chen 2019). A model-based robust control method of air supply systems (Figure 7(a)) is proposed for the PEM fuel cell based on the second-order sliding mode algorithm (J. Liu et al. 2019). A compound feed-forward PID control method (Figure 7(b)) for the air supply system with centrifugal compressors was proposed (Zhixiang Liu et al. 2016). A control solution based on dynamic disturbance decoupling control (DDC) (Figure 7 (c)) for an air supply system with a centrifugal compressor is studied (D. Zhao et al. 2013).

The surge is an important characteristic of centrifugal compressors. If centrifugal compressors operate under the surge condition, it would lead to the damage of compressors. A model reference adaptive control (MRAC) is introduced to avoid compressor surges during the dynamic operation of a PEM fuel cell system (Han, Sangseok, and Sun 2017) (Figure 7(d)).

3. Hydrogen supply system

The primary function of the hydrogen supply system is to feed the hydrogen gas to fuel cell stacks continuously with proper pressure. In PEM fuel cell systems, hydrogen gas is usually supplied from high-pressure tanks. Exhausted hydrogen can be reused by recirculation to improve the performance of PEM fuel cells. And the water in the anode channel can be managed by the control of the hydrogen flow rate.

3.1. Configurations of hydrogen supply system

There are four classic configurations of hydrogen supply systems (as shown in Figure 8). The detailed features of these four configurations are as follows:

(1) ***Flow-through method***. Figure 8(a) shows the method of hydrogen flowing through the fuel cell stack. The purge valve is opened at all time. The unreacted hydrogen is released directly into the atmosphere. In this operation mode, hydrogen flow must overcome the viscous forces of water droplets in fuel cell stacks, which leads to high fuel losses and safety risks. Hence, this method is less used in PEM fuel cells.

(2) ***Dead-end with period purge method***. Figure 8 (b) shows the dead-end method with a period purge. The purge valve is opened at a certain period. The close of the purge valve leads to an increase in the hydrogen utilization rate. But the decrease of the flow rate of hydrogen in the PEM fuel cell stack may cause the water flood of membranes and the going down of the performance of PEM fuel cells.

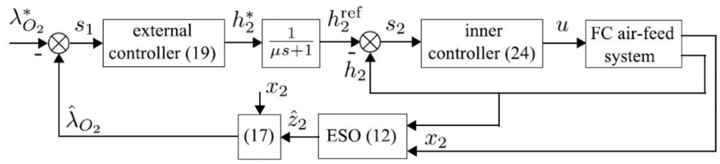
(3) ***Ejector recirculation with period purge method***. A hydrogen recirculation system with an ejector is shown in Figure 8(c). This layout circulates the unused hydrogen gas to the inlet of the fuel cell stack by an ejector. The ejector is driven by high-pressure hydrogen gas from the pressure valve. That means the recirculation energy is gotten from the inside of the hydrogen supply system, and no external energy supply is required.

(4) ***Compressor recirculation with period purge method.*** Figure 8(d) shows the anode active recirculation configuration with compressors (some references called pumps). This type of layout uses a compressor to circulate the unused hydrogen gas to the inlet of the fuel cell stack. And hydrogen utilization of this design is higher than those of the first two designs.

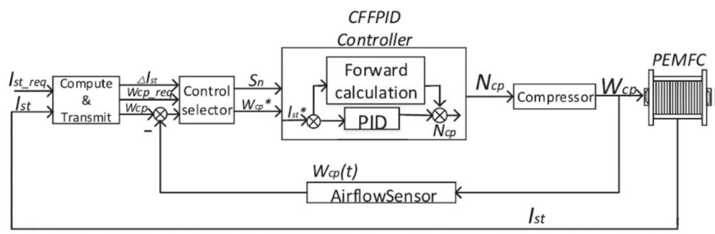
The recirculation methods can increase the mass flow rate of hydrogen in fuel cell stacks, which may avoid the water flood in the anode of fuel cells and increases hydrogen utilization.

The research shows that anode hydrogen can be severely diluted by nitrogen in pure recirculation without a purge valve (Promislow, St-Pierre, and Wetton 2011). To ensure the purity of hydrogen in fuel cell stacks, the purge valve is used for all kinds of hydrogen supply systems.

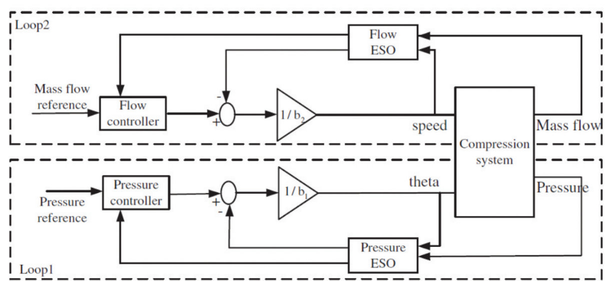
There are two kinds of purge strategies: discontinuous purge and continuous purge. The discontinuous method is based on discontinuous purge and uses the measured hydrogen content at the outlet of fuel cell stacks as a purge trigger. For the continuous method, the opening of the purge valve is controlled to purge continuously by using the parameter of hydrogen content at the stack outlet. The continuous purge strategy offers an efficient and robust solution to operate PEM fuel cells with up to 30 vol.% nitrogen content in the feed gas (Steinberger et al. 2018). An optimal pump recirculation system with a purging strategy is studied (Shen, Park, and Kim



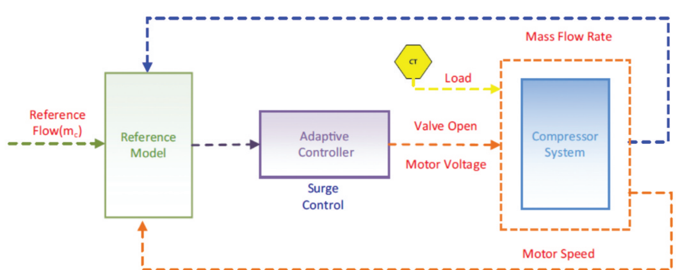
(a) Oxygen excess ratio control system (J. Liu et al. 2019)



(b) Compound feed-forward PID method (Zhixiang Liu et al. 2016)



(c) Diagram of the DDC method (D. Zhao et al. 2013)



(d) Schematic of the adaptive controller structure for surge control (Jaeyoung Han, Yu, and Yi 2017)

Figure 7. Typical control methods: (a) Oxygen excess ratio control system (J. Liu et al. 2019) (b) Compound feed-forward PID method (Zhixiang Liu et al. 2016) (c) Diagram of the DDC method (D. Zhao et al. 2013) (d) Schematic of the adaptive controller structure for surge control (Han, Sangseok, and Sun 2017).

2020). The results show that the hydrogen utilization rate is the highest when the purge time is 0.3 s and the purge period is 10 s.

For a PEM fuel cell initially operated with dry hydrogen, the anode recirculation leads to a certain level of performance increase in the beginning because of the self-humidification effect (Wang, Kangcheng, Yang, Jiao, 2018). The recirculation methods (Figure 8(c)and (d)) and end dead method (Figure 8 (b)) both have a self-humidification effect. Compared to the end dead method, the advantages of recirculation systems are the lower performance decline rate, less chance of local hydrogen starvation, and better current density distribution uniformity.

3.2. Recirculation equipment

As shown in Figure 8, there are two kinds of recirculation methods for the hydrogen supply system, i.e., the ejector recirculation and compressor recirculation. The major differences between compressor and ejector recirculation systems are as follows:

(1) ***Input power***. The input energy to ejectors comes from the high-pressure hydrogen that flows out of the pressure valve,

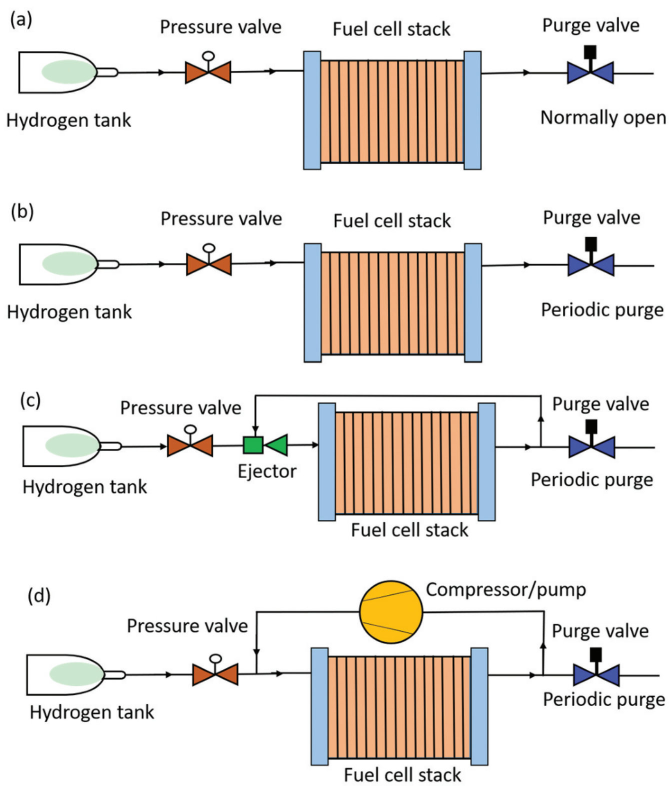


Figure 8. Typical hydrogen supply systems (Shen, Park, and Kim 2020): (a) Flow-through operation; (b) Dead-end with period purge; (c) Ejector recirculation with period purge; (d) Compressor recirculation with period purge.

which means no additional energy is imported from other systems. For the compressor recirculation system, additional energy is required to drive compressors, which results in a reduction in fuel cell efficiency.

(2) ***Operating range***. For recirculation systems, the range of recirculation ratios is the most critical parameter. Limited by the working principle of ejectors, the operating range of the system with ejectors is smaller than that with compressors. The rotation speed of compressors can easily be adjusted by frequency converters, leading to the wide operating range of hydrogen supply systems.

(3) ***Complexity of equipment***. Since there are no rotating or high-speed moving parts in the ejector, its structure is simple, and reliability is high when applied in PEM fuel cells. There are high-speed rotating parts in compressors, so the structure of compressors is complex, and the reliability of compressors is lower than that of ejectors.

3.2.1. Ejector

The operating principle of ejectors is that the pressure energy of the primary hydrogen from pressure valves is converted to velocity energy by adiabatic expansion in the nozzle. The pressure drop of the motive fluid creates a low-pressure zone before the mixing region. Due to the low-pressure zone, the secondary hydrogen (recirculation hydrogen) moves toward it and mixes with the primary hydrogen in the mixing region. Mixed hydrogen enters the diverging portion of the ejector, where its velocity energy is converted into pressure energy.

There are two kinds of ejectors, i.e., the fixed geometry ejector and variable geometry ejector (shown in Figure 9). For variable geometry ejector, a needle that can change the size of the primary nozzle opening is added to minimize performance loss and enhance its operating range. The research results show that the range of recirculation ratios under partial load conditions is 62.5–80% by controlling recirculation characteristics with the developed ejector using a needle (Baba et al. 2020).

The hydrogen supply system with the fixed geometry ejector is a passive recirculation system, and it is an active recirculation system when the variable geometry ejector is used.

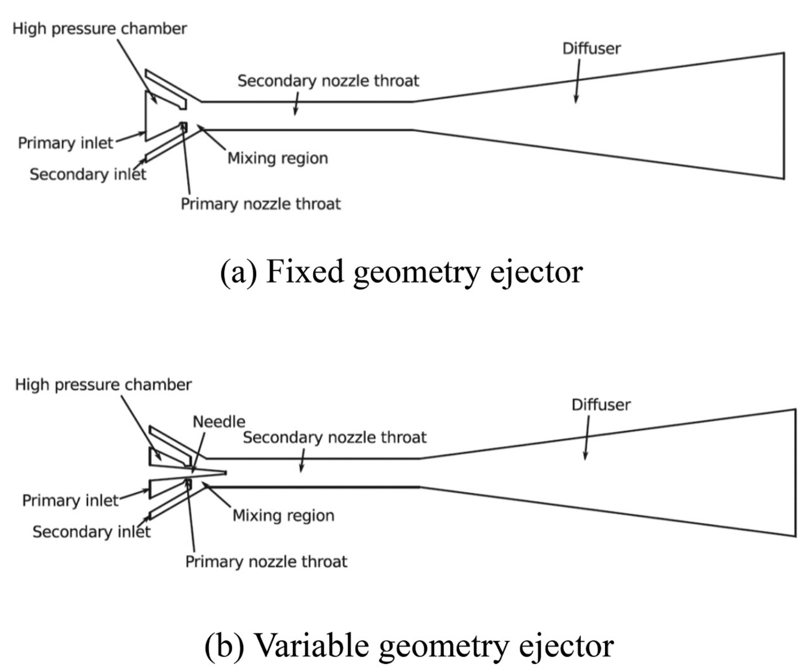


Figure 9. Basic structures of two ejectors (Brunner et al. 2012): (a) Fixed geometry ejector (b) Variable geometry ejector.

Many parameters affect the performance of ejectors, such as geometric parameters, anodic operating pressure, water vapor content in the secondary flow, anodic water flooding. The key characteristic of hydrogen ejectors is the operating range. The typical feature of ejectors is that a slight deviation from the optimum operating condition might drastically lower the performances of ejectors (Besagni et al. 2017). The primary geometric parameters are optimized to promote entrainment performance and extend the operating range of ejectors (Pei et al. 2019). Results show that the ejector hydrogen entrainment performance is sensitive to the nozzle diameter ratio to mixing tube diameter, and the optimal value range is 3.0–3.54. Water vapor has an important effect on the performance of the subsonic ejector for PEM fuel cells (F. Li et al. 2017).

Some models were proposed to simulate the performance of ejectors in PEM fuel cells. A one-equation model is proposed for the ejector in anode gas recirculation of solid oxide fuel cells (Zhu, Yanzhong, and Cai 2011). The proposed one-equation model only has one algebraic equation and four constant parameters, which is helpful for real-time control and optimization of fuel ejectors. A velocity function for analyzing the flow characteristics of ejectors is proposed by employing a two-dimensional concave exponential curve (Zhu and Yanzhong 2009). This treatment of velocity is an improvement compared to the conventional 1D "constant area mixing" or "constant pressure mixing" ejector theories.

The 3D numerical model based on the computational fluid dynamics (CFD) method is studied for ejectors (Y. Yin et al. 2016). The ejector geometric parameters are investigated and optimized. The smallest and largest hydrogen recirculation ratios are about 0.15 and 0.85, respectively. The ejector is used for the anode recirculation and hydrogen supply with the stoichiometry of at least 1.15 in the PEM fuel cells. Figure 10 shows the contour plots of the distribution of pressure, velocity, temperature, and mass fraction of water vapor in the ejector. Figure 11 shows the effects of the primary flow mass flow rate on the hydrogen recirculation ratio.

3.2.2. Hydrogen compressor

Compressors can recirculate the hydrogen gas by increasing the pressure of the recirculation gas. The mass flow rate of hydrogen gas can be controlled by changing the operating conditions of compressors easily. In theory, all kinds of compressors can be used as equipment for hydrogen recirculation. However, because the molecular weight of hydrogen gas is small, the design of centrifugal compressors for hydrogen recirculation in PEM fuel cells becomes very difficult. And positive displacement compressors are more suitable for PEM fuel cells for their ability to provide high pressure. Considering the requirements of PEM fuel cells and the characteristics of compressors, the side channel (regenerative), scroll, diaphragm, and draw compressor were researched and applied in PEM fuel cells. Besides, the electrochemical pump was introduced as the hydrogen compressor in PEM fuel cells.

A side channel blower was studied for the recirculation equipment of PEM fuel cells (Badami and Mura 2010) (Badami and Mura 2012). Its main structure is shown in Figure 12 (a). The test results show that the efficiency is less than 0.45 when the rotation speed is from 5,000 to 20,000 rpm, and the mass flow rate is from 0 to 3.5 g/s. Scroll compressors for PEM fuel cells were developed and studied by Zhang et al. (Qingqing Zhang et al. 2018a)(Qingqing Zhang et al. 2019), whose structure is shown in Figure 12 (b). The range of the rotation speed of the studied scroll compressor is 3,000–6,000 rpm. The results show that the leakage clearance has more effects on the performance of scroll compressors when the working fluid is changed from air to hydrogen. The diaphragm compressor can also be applied for the hydrogen recirculation in PEM fuel cells (Migliardini, Capasso, and

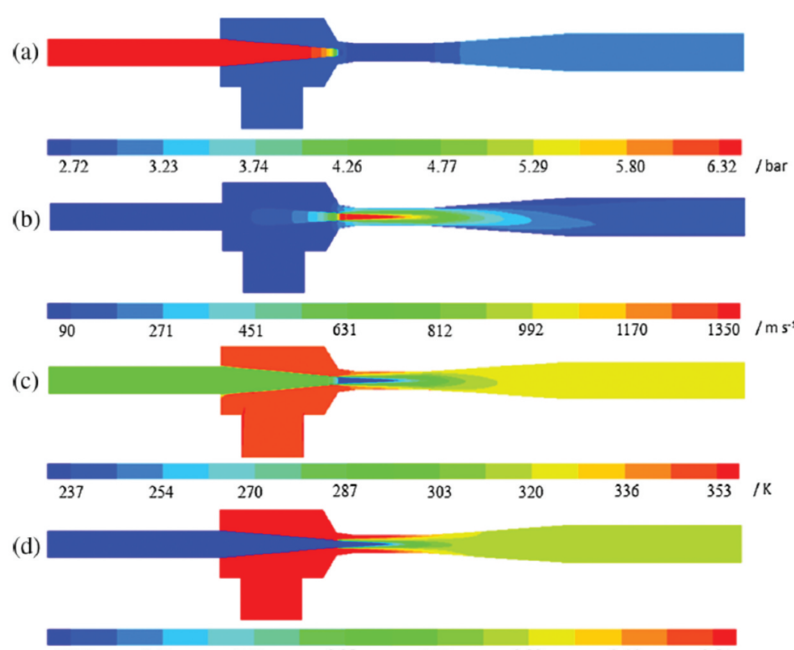


Figure 10. Contour plots for the distribution of (a) pressure, (b) velocity, (c) temperature, (d) mass fraction of water vapor in the middle z-plane (Y. Yin et al. 2016).

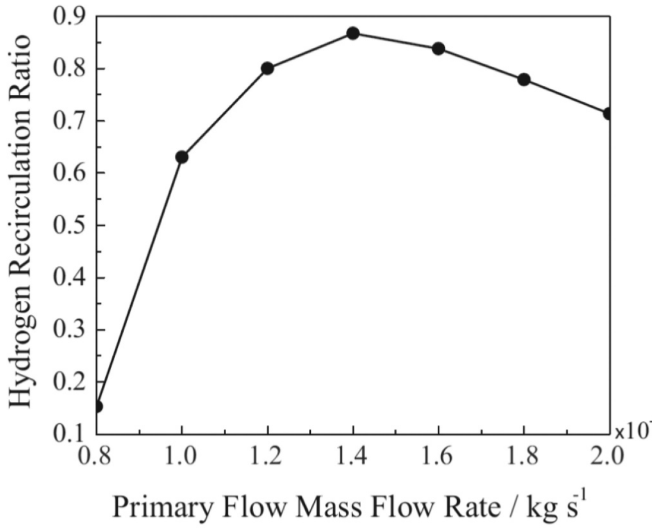


Figure 11. Effects of the primary flow mass flow rate on hydrogen recirculation ratio (Y. Yin et al. 2016).

Corbo 2014)(Migliardini et al. 2017). The pressure difference of the diaphragm compressor is 30–40 kPa in the references.

The electrochemical pump is analyzed in the hydrogen recirculation loop of a PEM fuel cell (Toghyani, Baniasadi, and Afshari 2018) (Toghyani, Afshari, and Baniasadi 2019) (shown in Figure 13). The efficiency of the hydrogen recirculation system with the electrochemical pump is close to the system with an ejector at low current density. At high current densities, the efficiency of the ejector is relatively higher than the electrochemical pump because the PEM fuel cell has a higher parasitic power that can be compensated using the ejector in the anodic recirculation system.

3.3. Control techniques

The primary control purpose of the hydrogen supply system is to achieve optimal system performance by changing the operating parameters of the hydrogen supply system. The hydrogen pressure, hydrogen recirculation rate, humidity, and nitrogen content are the main control parameters.

A hydrogen injection system using gaseous fuel injectors for regulating the anode pressure of PEM fuel cells was researched (C. Fang et al. 2015). A model-based controller is chosen for injection control to get the precise control of hydrogen

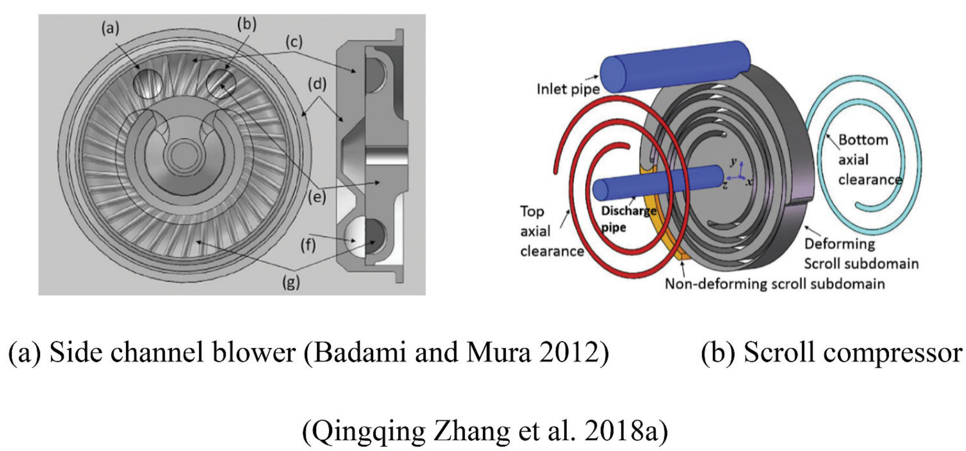


Figure 12. Structure of hydrogen compressors: (a) Side channel blower (Badami and Mura 2012) (b) Scroll compressor (Qingqing Zhang et al. 2018a).

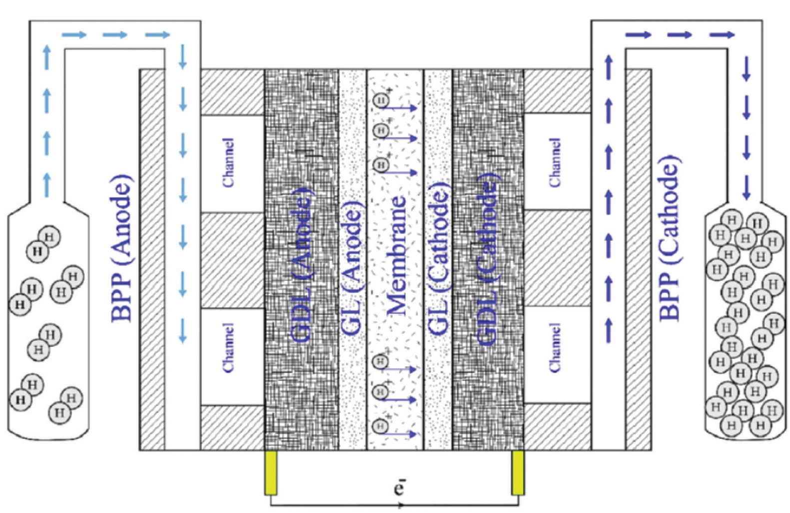


Figure 13. Cross-sectional view of electrochemical hydrogen pump (Toghyani, Baniasadi, and Afshari 2018).

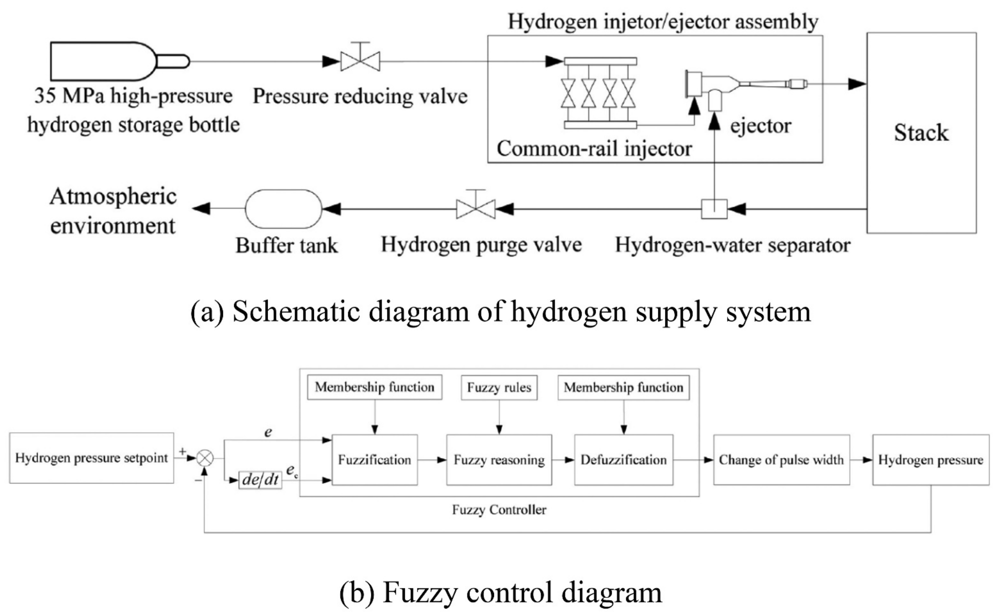


Figure 14. Schematic diagrams of hydrogen pressure control (Ye et al. 2019): (a) Schematic diagram of hydrogen supply system (b) Fuzzy control diagram.

pressure in fuel cell stacks. An improved common-rail injection system is introduced in the supply of hydrogen gas, and a Mamdani fuzzy controller is designed to regulate the hydrogen pressure (Ye et al. 2019). Figure 14 shows the schematic diagram of the hydrogen supply system and the fuzzy control method.

A model predictive control (MPC) approach for the hydrogen circulation system is developed (H. He, Quan, and Wang 2020). The research results indicate that the proposed MPC exhibits a better control performance with rapid response and good tracking accuracy even under disturbance variations.

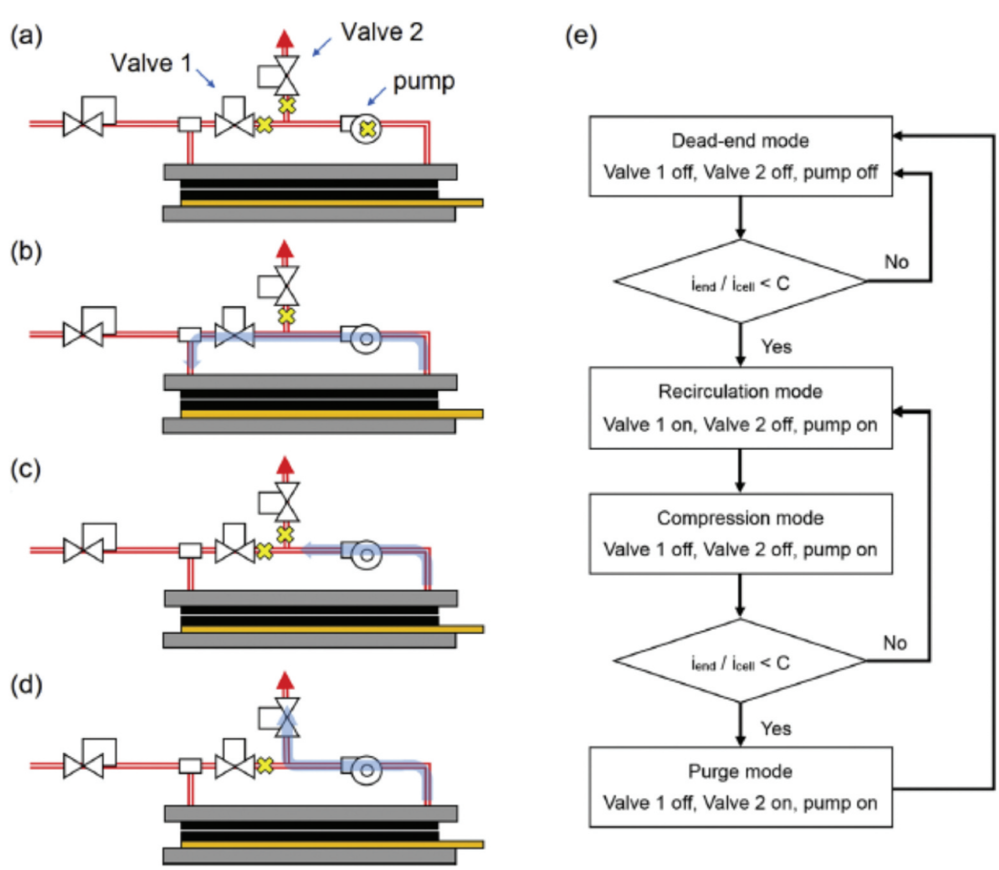


Figure 15. Anode configuration in (a) dead-end, (b) recirculation, (c) compression, (d) purge modes, and (e) gas management strategy (Lee, Su, and Chen 2018).

Impurities diffusing from the cathode to the anode may cause the dilution of hydrogen at the anode. Two valves are installed in the recirculation line (Figure 15) (Lee, Su, and Chen 2018). The anode is operated in four modes (dead-end, recirculation, compression, and purge), and the real-time local current density is monitored for gas management. With this configuration and gas management strategy, the cycle duration is increased by a factor of 6.5. The purge period can be extended from 40 min (simple dead-ended anode configuration) to 260 min (novel recirculation configuration with the gas management strategy) (Lee, Su, and Chen 2018).

Purge is necessary to remove the impurity from the PEM fuel cell stacks. Two basic purge strategies are voltage-based and nitrogen-based control methods (B. Wang, Deng, and Jiao 2018). For voltage-based purge control, the purge interval is defined by the voltage drop rate of the voltage peak. The voltage recovers firstly and then drops in the excess purge duration, so the optimal purge duration is defined as the purge stops when the voltage starts falling. The optimal purge duration is mainly determined by scavenging velocity. Energy efficiency and fuel loss rate both increase with the decreasing purge interval. For nitrogen-based purge control, the effect of purge duration on energy efficiency is much less significant than the purge interval. Due to the difficulty of the real-time nitrogen fraction measurement, the voltage-based purge is more recommended. An optimal bleed rate for energy efficiency exists, and a 3% bleed rate is optimal for the simulated operating conditions.

4. Recent progress in industrial applications

Some automobile companies brought new products to market in recent years, which use the PEM fuel cell systems as the drive engines. They are the Hyundai Nexo, Toyota Mirai, Honda Clarity, and so on. Some applications of gas supply systems of these automobiles are summarized as follows.

The first version of Toyota Mirai was put on the market in 2014, in which 6-lobe helical roots-type compressors are used, which are similar to screw compressors. And the maximum output power and speed are 20 kW and 12,500 rpm. The hydrogen pump of Toyota Mirai is 2-lobes straight roots-type, and the maximum output and speed of it are 430 W and 6,200 rpm. The gas supply system is upgraded for 2021 Mirai. The centrifugal air compressor with a speed of 183,700 rpm is instead of a 6-lobe helical roots-type compressor. Figure 16 shows the photos of these pieces of equipment.

air compressor (2014) air compressor (2021) hydrogen pump

A two-stage centrifugal compressor is used in Honda Clarity (Figure 17), in which the air bearing is used to get high rotation speed. Two gas injectors (with ejectors) are used in the hydrogen supply system to recycle the hydrogen from the fuel cell stack in Honda Clarity. The gas supply system of Hyundai Nexo is

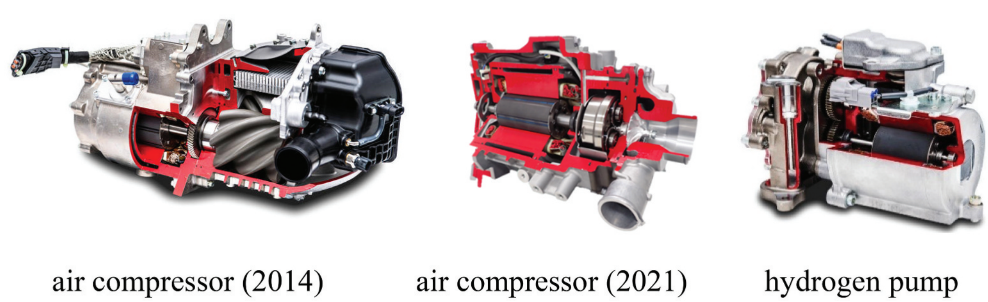


Figure 16. Air compressor and hydrogen pump for Mirai (Toyota 2021).

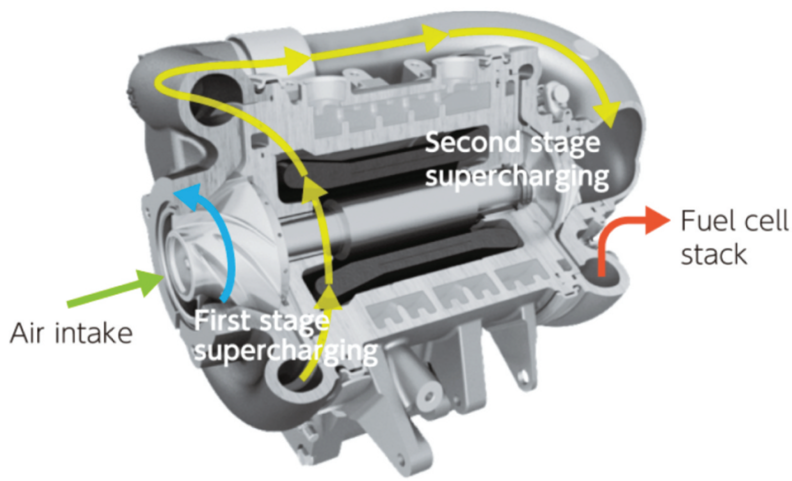


Figure 17. Centrifugal air compressor for Honda Clarity (Kerviel et al. 2018).

similar to that of Clarity, and the centrifugal air compressor and hydrogen ejector are used in the PEM fuel cell system.

5. Technical developing directions

5.1. Present challenges for gas supply systems

5.1.1. (1) Air supply system

Reduce energy consumption. The energy consumption ratio of air compressors is big for the PEM fuel cell systems. Reducing the energy consumption of air compressors is a method to improve the efficiency of the PEM fuel cell system. How to reduce the power of air compressors is a crucial challenge for these kinds of applications.

Device miniaturization. For mobile devices, small volume and weight are important for the air supply system, especially for air compressors. High rotation speed, new system design methods, and structural innovation of compressors are the important approaches.

Improve reliability. As fluid machinery, air compressors start and shut down with the PEM fuel cell frequently(Novotny et al. 2019)(Rabbani et al. 2014). The high reliability of air compressors is a crucial factor for the PEM fuel cell system. The compressed air should be oil free for the PEM. Hence, an oil-free air compressor is recommended. Up to now, some air compressors are not entirely without oil (for example, screw compressors and centrifugal compressors with mechanical accelerators).

5.2. (2) Hydrogen supply system

System simplification. Although many hydrogen supply systems have been applied in the actual PEM fuel cell systems, the performance of the hydrogen supply system needs to be improved continuously. The optimization of system design and control methods of devices (ejector, hydrogen compressor, and valves) is the main challenge for hydrogen supply systems.

Devices R&D. Unlike air compressors for air supply systems, the ejector and hydrogen compressor are entirely new designs for PEM fuel cells. The technical maturity of these devices is at a low level. Hence, the development of high-performance devices is a challenge.

5.3. Developing directions

5.3.1. (1) Coupling of air compressors with PEM fuel cell systems

Since the energy consumption of air supply systems accounts for a high proportion of the total energy consumption of PEM fuel cells, the operating parameters of PEM fuel cells and air compressors need to be coupled so that the performance of the entire system can be optimized.

The parameters of pressure, temperature, and mass flow rate of air supply systems affect the efficiency and power of PEM fuel cells. The working conditions are changing when PEM fuel cells are operated in actual working conditions, which leads to the operating conditions change of air compressors. When air compressors operate in different working conditions, the efficiency is changed (as shown in Figure 4). Therefore, we hope that the performance of compressors can be optimized under different operating conditions of PEM fuel cells.

Based on the simulation model of PEM fuel cells coupling with the detailed simulation model of air compressors, the detailed performance of PEM fuel cells would be gotten under different pressure, temperature, and mass flow rate. Hence, the optimum working conditions for air supply systems and PEM fuel cells could be obtained, which can guide the settings of PEM fuel cell control systems.

In terms of design, all operating conditions of PEM fuel cells should be considered in the design of air compressors. The parameters of air compressors should be optimized through the method of multiple operating points.

In terms of control, the surge of centrifugal compressors should be controlled firstly. Then, the primary purpose of the control of compressors is to meet the requirements of PEM fuel cells and to guarantee the high operating efficiency of compressors at the same time. Thus, the energy consumption of air supply systems could be reduced, and the efficiency of PEM fuel cells increases.

5.4. (2) Matching of compressor and expander in air supply system

The usage of expanders leads to the reduction of the energy consumption of air supply systems. But the research and development of expanders lag at present. Besides the development difficulty of expanders, another important reason is the matching technique of compressors and expanders. If these two devices are not matched properly, the energy consumption of the air supply system increases, and the efficiency of the PEM fuel cell system decreases.

When we design the air supply system with expanders, the operation parameters of the PEM fuel cell system should be considered firstly. Then, we should pay special attention to the operating parameters of compressors and expanders at the same time, especially the change of pressure and the mass flow rate. Thus, the matching design of two devices is the critical point to ensure that they can be operated under high-efficiency working conditions during most of the operating time.

5.5. (3) Integration of cooling and humidification in compressors

As mentioned above, if compressors are cooled during their working processes, the compression index of compressors would be reduced, and the consumption power of compressors decreases. Simultaneously, the temperature of the discharge air decreased, which reduce the heat exchange capacity of the gas cooler. Therefore, the cooling process of the compressor and the humidification process of air can be completed simultaneously by spraying water into compressors during the compression process.

When using the air supply system with water spray, many parameters (the mass flow rates of air and water, humidity, pressure, temperature, heat exchange capacity) are coupled in the same system. Usually, a large mass flow rate of spraying water leads to high humidity. But too much water in the compressed air results in much liquid water flows into the

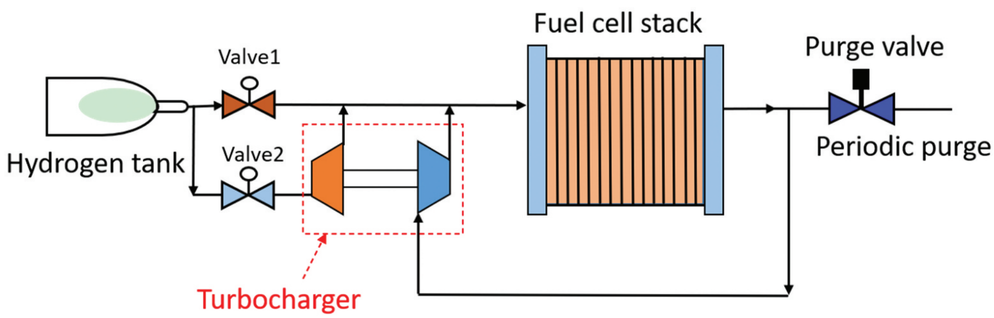


Figure 18. Hydrogen recirculation system with turbocharger.

PEM fuel cell stack. Hence, the mass flow rate of spraying water to compressors should be simulated under different working conditions (pressure, temperature, and mass flow rate of air).

Based on the working principle and structure features, it is permitted to spray water into compression chambers of positive displacement compressors. For centrifugal compressors, some researchers have studied the water injection into the inlet of compressors. Therefore, it may be a new research direction to carry out the water injection centrifugal compressor.

5.6. (4) Energy utilization of high-pressure hydrogen gas

In many PEM fuel cells of automobiles, the hydrogen gas is stored in high-pressure tanks with a storage pressure of up to 70 MPa (M. Li et al. 2019). The utilization of the pressure energy of the hydrogen gas would improve the performance of PEM fuel cell systems. In the hydrogen recirculation system with an ejector, the energy to drive the entire cycle is the pressure energy of hydrogen gas with high pressure.

Because there is an operating range limit for the hydrogen recirculation system with an ejector, the hydrogen-driven turbocharger (as shown in Figure 18) is introduced in this paper to use the pressure energy of hydrogen gas. The turbocharger is composed of the micro-turbine and centrifugal compressor. Its working principle is as follows:

Through Valve 1, some high-pressure hydrogen gas in the hydrogen tank decompresses to the pressure of fuel cell stacks. Other hydrogen gas decompresses through Valve 2, and then the hydrogen gas flows into the micro-turbine. In the turbine, the hydrogen gas is expanded, and the value of pressure decreases to the pressure of fuel cell stacks. The power generated during the expansion process drives the compressor to compress the recirculation hydrogen gas from the exhaust pressure to the supply pressure of the fuel cell stacks. The mass flow rate of hydrogen gas in the hydrogen circulation system can be changed by adjusting the mass flow rate of hydrogen gas from the hydrogen tank (changing the opening of Valve 2).

Compared with the recirculation system with ejectors, the recirculation system with turbochargers has better regulating performance. Compared to the recirculation system with hydrogen compressors, no external energy is required to drive this system. Hence, the design, performance simulation, and control method of hydrogen turbochargers could be the detailed research directions in the future.

6. Conclusions

Air and hydrogen supply systems are essential subsystems for PEM fuel cells, which have significant effects on the performance of PEM fuel cell systems. This paper reviews the research on air and hydrogen supply systems and equipment for PEM fuel cells over the past decades.

For air supply systems, the research of air compressors has been reviewed. The scroll, screw, Roots, and centrifugal compressors are major structures applied in the PEM fuel cells. Most studies focused on the control of the air supply system with centrifugal compressors. The performance difference between the positive displacement and centrifugal compressors was compared. Water injection to compressors is a workable method to humidify the air in the working chamber of compressors.

Four configurations of hydrogen supply systems are introduced, i.e., the flow-through, dead-end with a period purge, ejector recirculation with period purge, and compressor recirculation with a period purge method. The research on recirculation equipment is summarized. The characteristics of ejectors and hydrogen compressors are presented. The hydrogen pressure, hydrogen recirculation rate, humidity and water in fuel cell stacks, and nitrogen content are the main control parameters of the hydrogen supply system.

The main technical developing directions for gas supply systems of PEM fuel cells have been presented. These key techniques involve the coupling research of air compressors with PEM fuel cell systems, matching research of the compressor and expander in the air supply system, integration of cooling and humidification in compressors, and energy utilization of high-pressure hydrogen gas.

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