SCIENCE CHINA
Information Sciences

• REVIEW •

May 2019, Vol. 62 051201:1–051201:25
https://doi.org/10.1007/s11432-018-9690-y

Challenges and developments of automotive fuel cell hybrid power system and control

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Received 11 June 2018/Revised 11 October 2018/Accepted 7 November 2018/Published online 1 April 2019

Abstract Fuel cells are emerging as promising power sources and have attracted increasing attention from industries and academics worldwide. In particular, automotive manufacturers are replacing internal combustion engines in vehicles with fuel cell systems, which are advantaged by zero emissions, high efficiency, and various clean routes that generate pure hydrogen. However, current fuel cell systems are costly, and their corresponding infrastructures are not fully qualified to meet current market demand. This paper reviews the challenges and developments of automotive fuel cell hybrid power systems and their controls. It briefly summarizes the model, control, and optimization issue associated with the research and application of fuel cells in hybrid power systems. After presenting the basic knowledge and discussing the trending size and structure of fuel cells for automotive usage, the review describes models of automotive fuel cell systems, focusing on the electrochemical reaction dynamics and the key parameters influencing their efficiency and lifetime. The control problems associated with automotive fuel cell systems as well as the optimization issue associated with hybrid energy systems (comprising fuel cells, batteries, and ultra-capacitors) are elaborately analyzed. The review concludes with current problems and challenges faced by the energy control systems of fuel cell vehicles.

Keywords fuel cell system, automotive fuel cell control, optimization issue, hybrid energy system

Citation Gao J W, Li M, Hu Y F, et al. Challenges and developments of automotive fuel cell hybrid power system and control. Sci China Inf Sci, 2019, 62(5): 051201, https://doi.org/10.1007/s11432-018-9690-y

1 Introduction

For over 100 years, fossil-fueled transportation has improved human being's life and promoted economic development. Currently, automobiles are a worldwide necessity and consume a large part of the Earth's energy. According to the US Energy Information Administration (EIA), transportation accounted for 29% of energy consumed by the US in 2015, which is only 3% less than the industrial energy consumption [1]. Consequently, transportation contributes air pollutants and green-house gases a lot compared to other human activities. To reduce automotive emissions, replacing fossil fuel energy by clean and renewable energy sources is becoming crucial and necessary.

Among various alternative energy sources and technologies, hydrogen and fuel cells are considered as promising solutions for achieving the zero-emission goal. There exist mainly three advantages of hydrogen energy. First, hydrogen consumption releases only harmless water from the exhaust. Second, liquid hydrogen contains more chemical energy than the same amount of fossil fuel, does not degrade over long-term storage, and gets charged quickly. Finally, hydrogen is plentiful on Earth and can be produced by other renewable and sustainable energy sources, providing an important contribution toward meeting

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carbon targets. To promote the development of hydrogen generation and fuel cells, the major countries, unions, and districts have offered their blueprints or roadmaps for hydrogen production and usage [2–7].

Fuel cells directly convert the chemical energy of hydrogen into electrical energy, water, and heat. Modern applications, including distributed generation, vehicles, and telecommunication applications are mainly powered by six types of fuel cells [8, 9]. Among these fuel cells, proton-exchange membrane fuel cells (PEMFCs) are popular and widely installed in automotive vehicles because of their low operating temperature, quick start-up capability, rapid response to load changes, and high efficiency (theoretically 83% but in practice around 50%) [10]. After considerable efforts on developing their fuel cell design and control technology, PEMFCs have reached the 2009 targets of the US Department of Energy (DoE), i.e., 5000 h operation for passenger cars and 10000 h operation for buses. The cost of manufacturing PEMFC vehicles has decreased by 90% since 2005 [11]. In a recent fuel cell demonstration [12], an electric vehicle operated for more than 20000 h in a real-world service without any cell replacement. The real-life target is 5000 h operation before 2020 (equivalent to 150000 miles of driving), ultimately increasing to 8000 h operation with less than 10% performance losses under dynamic load following, start/stop operations and other functions. Although literature reports on these targets are lacking, the comparative performance indicators of PEMFCs, e.g., power density, specific power cost, and cold start time, have been updated [13].

Over the past few years, electric buses based on hydrogen fuel cells have greatly advanced worldwide and are operating with zero local emissions, reduced noise, and reduced emissions on a well-to-wheel basis [14]. The most aggressive promoters of fuel cell vehicles (FCVs) are Toyota and Honda in Japan and Hyundai in Korea. Toyota's Mirai FCV, Honda's Clarity FCV, and Hyundai's Tucson (ix35) and NEXO FCVs are commercially available. Although hydrogen is probably regarded as ultimate energy form for transportation and fuel cells, especially PEMFC plays a key role in powertrain system, there is still a large potential to improve PEMFC system so that the day winning the traditional internal combustion engines (ICEs) can arrive sooner. Research on the durability, packaging, key components, and cost reduction of fuel cells is underway, but the air–hydrogen supply, transient power response, efficiency optimization, cold start, thermal management, and humidity control must be perfected to realize the true potential of fuel cells.

This paper reviews the challenges and recent developments of fuel cell control for automotive applications. It first introduces the structure, working principle, and special requirements of PEMFCs used in electric vehicles. With this knowledge, we can better understand the effective control of fuel cell systems and why many improvements are needed. PEMFC models, including the air path dynamics, electrochemical dynamics, thermal dynamics, and other subsystems, are then discussed in detail. This discussion will assist readers to understand the control objective and controller synthesis. Various control issues and strategies implemented in automotive PEMFC control systems are then elaborated. The review concludes with open problems and challenges faced by the energy systems of FCVs.

2 Structure and working principle of fuel cells for automotive application

Unlike traditional and hybrid vehicles, which are driven by combustion of ICEs and electric generators, respectively, FCVs generate electricity through electrochemical reactions. The generated electricity directly drives the vehicle through the motor or is temporarily saved in storage compartments, e.g., batteries or super capacity packs. Figure 1 shows the typical structure of a fuel cell, which usually comprises a hydrogen and air supply system, a fuel cell pack, a cooling system, a humidity management system, an electric load system, and a hydrogen storage tank.

The powerhouse of the fuel cell is the fuel cell stack, which performs the electrochemical reaction and transforms chemical energy directly to electricity. The stack comprises two catalyst layers separated by a PEM layer and sandwiched between two flow plates. At a proper hydrogen–oxygen ratio and pressure, hydrogen in the fuel cell stack is catalyzed into hydrogen ions and electrons in the presence of a platinum catalyst. The hydrogen ions are admitted by the PEM to the cathode, where they are oxidized to water.

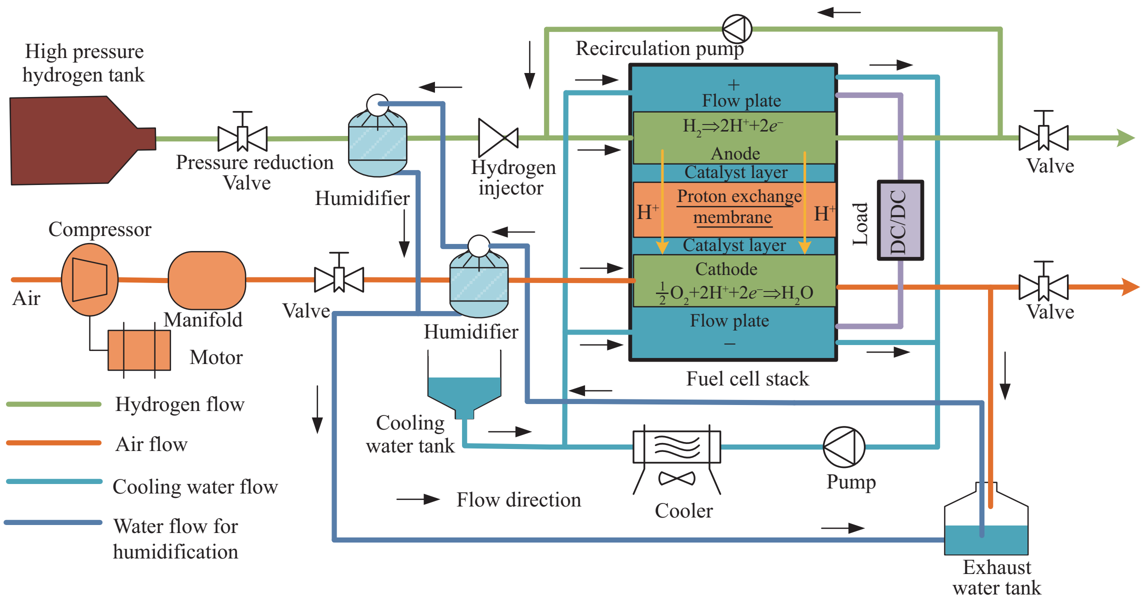

Figure 1 (Color online) Typical structure of a fuel cell.

At the same time, the electrons are forced pass through an external DC/DC circuit to the cathode. To maintain an efficient, continuous, and stable electrochemical reaction in the fuel cell stack, the fuel cell temperature and current density, humidity of the PEM, hydrogen–oxygen ratio, and their accompanying pressures must be controlled in a coordinated manner. Otherwise, the demanded durability and efficiency of the fuel cell cannot be ensured.

Hydrogen is tanked at a high pressure (up to 35 or 70 MPa), but it remains in the gaseous state. Gaseous hydrogen at the desired pressure is packed into the fuel cell through a pressure reduction valve, which is precisely controlled between the hydrogen tank and the fuel cell stack. Meanwhile, residual hydrogen passing through the anode of the fuel cell stack is pumped back to the entrance of the hydrogen pipeline by a recirculation pump. By this mechanism, hydrogen is almost 100% oxidized (Refs. [15, 16] reported hydrogen utilizations of up to 96% and 99.6%, respectively) for electricity generation. The air supply system generates a very large flow of high-pressure air using a compressor driven by a high-speed motor. In automotive applications, the generated power can exceed 10 kW. After passing through the manifold, the pressurized air enters the cathode and is directly exhausted to the environment via a controlled valve. The humidity of the PEM is usually adjusted by humidifiers placed before the entrances of the hydrogen and air pipelines. However, advanced automotive manufacturers are trying to reduce the size of fuel cells by removing the humidifiers while still controlling the humidity of the PEM [17].

In most cases, especially in high-power mode of the fuel cell, waste heat generated by the electrochemical reaction increases the temperature of the fuel cell stack. According to the PEMFC characteristics, temperature should be controlled at approximately 60°C–80°C. Therefore, a cooling system is indispensable for extracting heat from the fuel cell stack. The cooling system comprises a pump and cooler, a cooling water tank, and its corresponding pipeline. As shown in Figure 1, the propulsive force of the pump circulates the cooling water between the flow plate of the fuel cell stack and the cooler. The temperature of the fuel cell stack is controlled by adjusting the speeds of the pump and the cooler fan.

Unlike other applications, e.g., portable batteries and power stations, automotive applications are demanding compact fuel cells that can be installed in limited-size engine compartments such as traditional ICEs. The body structure of an electric vehicle is almost identical to those of conventional vehicles and hybrid electric vehicles (HEVs). As shown in Figure 2, the famous Toyota Mirai fuel cell car still uses a distributed fuel cell, but advanced automotive manufacturers are increasingly aiming to commercialize fuel cell powertrains that resemble familiar engines.

As most FCVs have an onboard temporary energy storage system (ESS), they are similar to HEVs.

Figure 2 (Color online) Compact fuel cells developed by advanced automotive manufacturers. (a) Mercedes-Benz fuel cell; (b) Honda fuel cell; (c) BMW fuel cell; (d) Hyundai fuel cell.

Specifically, the fuel cells of an FCV perform the same roles as the powertrain units of an HEV. Similar to the HEV structure, the usual ESS of an FCV is a battery that can be charged and discharged according to the power demand and supply. Figure 3 shows a typical powertrain of the FCVs used in [18, 19]. In applications such as forklifts and submarines, the power demands are almost constant and ESS can be reduced or even removed. In contrast, ESS is very important for the bus and passenger cars because the high requirement on power performance and drivability asks for the abrupt change in power demand, which would be out of the dynamics of fuel cell. In FCVs, ESS acts as a buffer providing an instant power source. The battery, which is incorporated as part of the powertrain, avoids the wait between the power demand and warm-up of the fuel cell.

The size of the ESS affects the required dynamics of the fuel cell. If a large-capacity ESS is available, it usually supplies the transient power demand and the fuel cell can work as a range extender under constant load. In contrast, a small-capacity ESS cannot meet the major abrupt change of the power demand. Therefore, a high-performance fuel cell is required, which increases the difficulty of the cell design and control. With the development of fuel cell control technology, modern fuel cells, e.g., those used in Toyota Mirai [17], can respond to rapid changes in power demand, so a small-sized ESS can reach the market requirement. However, the durability and controller design of the fuel cell system becomes challenging in this scenario.

Another special requirement of automotive fuel cell control is the cold start process. Vehicles should operate under various operating conditions, e.g., hot and humid environments, very low temperatures, high salt environments along the coast, and thin air environments on plateaus. Starting a fuel cell system

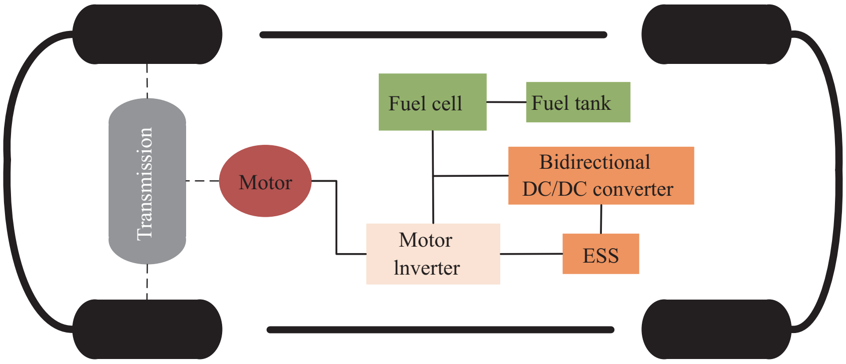

Figure 3 (Color online) A typical powertrain of FCVs.

at considerably low temperatures (below 0°C) is quite difficult. If the temperature of the PEM and catalyst layer cannot rise above freezing point, the electrochemical reaction will be prevented by ice and the fuel cell will probably be damaged due to inflation as the phase transforms from water to ice [20]. Thus, starting the fuel cells at low temperatures and maximizing their power output are important but challenging problems.

3 Modeling of automotive fuel cell systems

Hydrogen in the fuel cell stack is fed to the anode and is divided into hydrogen ions and electrons upon reaching the catalyst. The electrons are then forced outside the stack via an external circuit, which creates the electric current that drives the vehicle or charges ESS. Meanwhile, water generated by oxidizing hydrogen is expelled through the exhaust. Research has revealed that electrochemical reaction is highly influenced by the air-hydrogen supply as well as by the humidity and temperature of the PEM. Modeling these influences in the fuel cell stack is quite complicated.

To precisely depict the dynamics of the fuel cell stack, we discuss several models with different complexities. For example, in [21], a model for heat and water transportation was developed for evaluation with regard to different structures and materials. Steady-state and dynamic voltage-current mathematical models were studied in [22]. The performance prediction of a fuel sell system using backpropagation and radial-basis function networks was done in [23]. Water transportation has also been described in a complicated seven-layer theoretical model [24], whereas fluid flow, heat transfer, and other transport phenomena have been simulated in a general model constructed from partial differential equations [25]. Some studies have developed current distribution models, dynamical models with temperature effects, conductive transportation models, and thermal models [26–31]. In summary, the models of fuel cell systems can be divided into several parts excluding auxiliary components, namely, electrochemical reaction models, air-hydrogen supply models, thermal models and humidity models. The control-oriented models of fuel cell stack will be discussed as follows.

The definitions of variables below in Section 3 can be found in Appendix A.

3.1 Electrochemical reaction model

The electrochemical reaction model of fuel cell stack focuses on the relation between power output of fuel cell, exhaust water and inputs such as hydrogen-air supply and some key states or parameters like temperature and humidity of PEM. In detail, the open loop voltage of fuel cell is obtained based on energy balance between chemical energy and electrical energy. In [32], the open-loop voltage is given by

$$E = 1.229 - 0.00085(T_{\rm fc} - 298.15) + 4.3085 \times 10^{-5} T_{\rm fc} \left[\ln(p_{\rm H_2,an}) + \frac{1}{2} \ln(p_{\rm O_2,ca}) \right]. \tag{1}$$

There are three main losses in the fuel cell system: activation loss, ohmic loss, and concentration loss.

For the activation loss, the overvoltage is modeled as the following function of current in [33]:

$$v_{\mathrm{act}} = v_0 + v_a \left(1 - \mathrm{e}^{-c_1 i}\right), \tag{2}$$

where v_0 is the voltage drop at zero current density, v_a and c_1 are constants dependent on the oxygen partial pressure and temperature. i is the current density in the fuel cell, which is equal to

$$i = \frac{I_{\mathrm{st}}}{A_{\mathrm{fc}}}.$$

Ohmic loss is caused by resistance of the proton membrane. The voltage drop obeys Ohm's law as follows:

$$v_{\mathrm{ohm}} = i \times R_{\mathrm{ohm}},$$

where R_{ohm} is the internal electrical resistance [34] given by

$$R_{\mathrm{ohm}} = \frac{t_m}{\sigma_m},$$

with

$$\sigma_m = b_1 \exp\left(b_2\left(\frac{1}{303} - \frac{1}{T_{\mathrm{fc}}}\right)\right),$$

where b_1 is a function of the membrane humidity and b_2 is a constant.

The concentration loss changes the concentrations of the cell reactants [35]. The resulting overvoltage is modeled as

$$v_{\mathrm{conc}} = i\left(c_2 \frac{i}{i_{\max}}\right)^{c_3}, \tag{3}$$

where c_2, c_3, and $i_{\max}$ are empirical parameters that depend on the temperature and reactant partial pressure. Considering all above electrochemical reactions and losses, the output voltage of fuel cell v_{out} can be expressed as

$$v_{\mathrm{out}} = E - v_{\mathrm{act}} - v_{\mathrm{ohm}} - v_{\mathrm{conc}}. \tag{4}$$

It should be noted that the above electric model assumes a steady fuel cell in which the dynamics are ignored. In [36], the rapid dynamic behavior called "charge double layer" phenomenon was discussed. However, according to the results of [37], the steady-state electric model of the fuel cell is reasonable because the transient dynamics are faster than the air path dynamics.

When the fuel cell generates electric power, it simultaneously consumes oxygen and hydrogen. The rates of oxygen and hydrogen consumption and that of water generation are based on electrochemical principles and are given by

$$W_{\mathrm{H_2,comsum}} = M_{\mathrm{H_2}} \times \frac{nI_{\mathrm{st}}}{2F}, \tag{5}$$

$$W_{\mathrm{O_2,comsum}} = M_{\mathrm{O_2}} \times \frac{nI_{\mathrm{st}}}{4F}, \tag{6}$$

and

$$W_{\mathrm{wat,cagen}} = M_{\mathrm{wat}} \times \frac{nI_{\mathrm{st}}}{2F}, \tag{7}$$

respectively.

3.2 Air-hydrogen supply model

The air and hydrogen dynamics in fuel cell control are modeled based on the ideal gas law. In the air and hydrogen supply path, the pressures of hydrogen, oxygen in anode, cathode and the pressure of total cathode depend on the inlet, outlet, and consumed flow rates and are given by

$$\dot{p}_{\mathrm{H_2,an}} = \frac{T_{\mathrm{hy}} R_{\mathrm{H_2}}}{V_{\mathrm{an}}} (W_{\mathrm{an,in}} - W_{\mathrm{H_2,consum}} - W_{\mathrm{an,out}}), \tag{8}$$

$$\dot{p}_{\mathrm{O_2,ca}} = \frac{T_{\mathrm{air}} R_{\mathrm{O_2}}}{V_{\mathrm{ca}}} (W_{\mathrm{ca,in}} x_{\mathrm{O_2,in}} - W_{\mathrm{O_2,consum}} - W_{\mathrm{ca,out}} x_{\mathrm{O_2,out}}), \tag{9}$$

$$\dot{p}_{\mathrm{ca}} = \frac{T_{\mathrm{air}} R_a}{V_{\mathrm{ca}}} (W_{\mathrm{ca,in}} - W_{\mathrm{O_2,consum}} - W_{\mathrm{ca,out}}), \tag{10}$$

where $x_{\mathrm{O_2,in}}$ and $x_{\mathrm{O_2,out}}$ represent the oxygen mass fractions of the air flowing into and out of the cathode, respectively [36]. The variables $W_{\mathrm{H_2,consum}}$ and $W_{\mathrm{O_2,consum}}$ have been defined in Eqs. (5) and (6), respectively.

When supplying hydrogen in a working fuel cell, the exhaust valve is closed and hydrogen is recirculated through the pump. Therefore, we may reasonably assume that

$$W_{\mathrm{an,out}} = 0.$$

$W_{\mathrm{an,in}}$ is then given by

$$W_{\mathrm{an,in}} = k_1 (p_{\mathrm{H_2,supply}} - p_{\mathrm{H_2,an}}),$$

where parameter k_1 is controlled by the hydrogen injector.

As in an ICE, the air path system largely determines the dynamics and output power of the fuel cell system. Unlike a hydrogen supply system, a fuel cell system requires control of both the air pressure and concentration of oxygen in the cathode manifold. If this control is not exercised, the compressor and exhaust valve cannot cooperate to ensure an acceptable performance of the fuel cell. The dynamics of the supply and return manifolds (see Figure 4) are usually modeled by the nozzle flow equation [38]. The details are described in [36]. In FCVs, the volume of the cathode manifold exceeds that of the return manifold, so the dynamics of the return manifold can be neglected. We therefore have

$$W_{\mathrm{ca,out}} = W_{\mathrm{rm,out}} = \frac{C_d A_1 p_{\mathrm{atm}}}{\sqrt{R T_{\mathrm{rm}}}} \left(\frac{p_{\mathrm{atm}}}{p_{\mathrm{ca}}}\right)^{-\gamma} \sqrt{\frac{2\gamma}{\gamma-1}\left[1-\left(\frac{p_{\mathrm{atm}}}{p_{\mathrm{ca}}}\right)\right]^{\frac{\gamma-1}{\gamma}}},$$

when

$$\frac{p_{\mathrm{atm}}}{p_{\mathrm{ca}}} > \left(\frac{2}{\gamma+1}\right)^{\frac{\gamma}{\gamma-1}},$$

and

$$W_{\mathrm{ca,out}} = W_{\mathrm{rm,out}} = \frac{C_d A_1 p_{\mathrm{ca}}}{\sqrt{R T_{\mathrm{rm}}}} \sqrt{\gamma \left(\frac{2}{\gamma+1}\right)^{\frac{\gamma}{\gamma-1}}},$$

when

$$\frac{p_{\mathrm{atm}}}{p_{\mathrm{ca}}} \leqslant \left(\frac{2}{\gamma+1}\right)^{\frac{\gamma}{\gamma-1}}.$$

The air mass flow across the engine throttle is also widely modeled by the nozzle flow equation. By the same deduction as above, $W_{\mathrm{ca,in}}$ can be modeled using the nozzle flow equation and the compressor

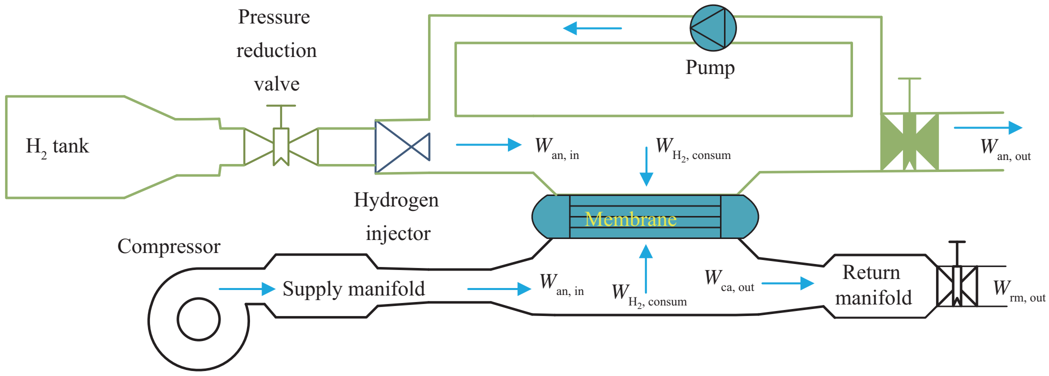

Figure 4 (Color online) Air-hydrogen supply subsystem.

dynamics (the derivation is not further discussed).

3.3 Thermal model

Ideally, thermal model of fuel cell stack should be parameter-distributed so that it is possible to precisely describe and predict the temperature distribution of fuel cell. However, although distributed models are widely applied in numerical simulations, they are unsuitable for controller synthesis. To grasp the major thermal dynamics of the fuel cell stack in simple terms, a lumped transient thermal model of fuel cell stack is explained in [39]. According to energy conservation of PEM fuel cell stack, it is known that

$$c_{\rm fc} m_{\rm fc} \dot{T}_{\rm fc} = W_{\rm fc,gen} - W_{\rm conv,gas} - W_{\rm conv,cool}. \tag{11}$$

Based on the electric model of the fuel cell, $W_{\rm fc,gen}$ can be calculated as follows:

$$W_{\rm fc,gen} = (v_{\rm act} + v_{\rm ohm} + v_{\rm conc}) \times i \times n.$$

Meanwhile, the heat transferred to the gas and cooling water is given by

$$W_{\rm conv,gas} = h_{\rm conv,air} A_{\rm conv,air} \left(T_{\rm fc} - \frac{T_{g,o} + T_{g,i}}{2} \right), \tag{12}$$

$$W_{\rm conv,cool} = h_{{\rm conv},c} A_{{\rm conv},c} \left(T_{\rm fc} - \frac{T_{c,o} + T_{c,i}}{2} \right), \tag{13}$$

respectively. In Eqs. (12) and (13), $h_{\rm conv,air}$ and $h_{{\rm conv},c}$ largely depend on the mechanical geometry of the fuel cell, convection area, and the type and rate of flow [39], so it is difficult to obtain their exact values. However, if temperature sensors for measuring the air and cooling water temperatures are available, $W_{\rm conv,gas}$ and $W_{\rm conv,cool}$ can be calculated as

$$W_{\rm conv,gas} = c_{\rm air,out} \rho_{\rm air,out} W_{\rm air,flow} T_{g,o} - c_{\rm air,in} \rho_{\rm air,in} W_{\rm air,flow} T_{g,i},$$

$$W_{\rm conv,cool} = c_{\rm cool} \rho_{\rm cool} W_{\rm cool,flow} (T_{c,o} - T_{c,i}),$$

respectively. In the thermal model, $W_{\rm cool,flow}$ can be controlled to hold the temperature of the fuel cell stack under various loads and airflows. This is realized by adjusting the cooling pump and rotation speed of the cooler fan.

The lumped-parameter dynamic model described above sufficiently models the heat and temperature of the fuel cell stack. Structured components, e.g., water pump, cooling fan, and radiator, require a component model of the thermal management system [30]. In [40], an electric equivalent circuit of the single-cell thermal model is introduced, which captures the dynamics of the power battery using a fractional-order model [41]. This model can depict the temperature dynamics of the plates in the fuel-cell stack and the variations in the heat delivered to the stack. In order to trade off the model complexity and accuracy, Ref. [42] designed a control-oriented model using a modular approach, which computes the temperature variations in each cell in the stack. A similar 16th-order cell temperature model of a PEMFC stack was developed in [43]. These three models aimed to achieve accuracy higher than lumped-parameter dynamics models, but their parameter identification and verification require further work.

3.4 Humidity model

According to experimental results of [34], the water concentration in the membrane is determined by the relative humidity of the unflooded anode and cathode sides

$$\lambda_m = 0.043 + 17.81a_m - 39.85a_m^2 + 36.0a_m^3,$$

where a_m is the relative humidity of the membrane that can be obtained by

$$a_m = \frac{a_{\text{an}} + a_{\text{ca}}}{2}.$$

The above membrane humidity model should be accompanied by another model that describes the flow rate of the water mass across the membrane from cathode to anode. Such a model is given by [34,36]

$$W_{\text{wat,mem}} = N_{\text{wat,mem}} \times M_{\text{wat}} \times A_{\text{fc}} \times n,$$

where parameter $N_{\text{wat,mem}}$ depends on the membrane thickness, water content in the membrane, diffusion coefficient of the membrane, and total current. It is calculated as

$$N_{\text{wat,mem}} = n_d \frac{i}{F} - D_w \frac{c_{\text{wat,ca}} - c_{\text{wat,an}}}{t_m},$$

where $c_{\text{wat,ca}}$ and $c_{\text{wat,an}}$ represent the water concentrations at the cathode and anode sides of the membrane, respectively. Assuming that no liquid water exists in the fuel cell stack, the water vapor flows through the anode and cathode channels calculated as

$$W_{\text{wat,an}} = W_{\text{wat,an,in}} + W_{\text{wat,mem}},$$

$$W_{\text{wat,ca}} = W_{\text{wat,ca,in}} + W_{\text{wat,cagen}} - W_{\text{wat,mem}},$$

respectively, where $W_{\text{wat,cagen}}$ can be calculated using (7). Apparently, the membrane humidity can be controlled by regulating $W_{\text{wat,an,in}}$ and $W_{\text{wat,ca,in}}$ at different temperatures and loads of the fuel cell system.

To model the dynamics of whole fuel cell systems in automotive applications, the abovementioned models should be supplemented by models of auxiliary components, e.g., compressors, humidifiers, cooling systems, and various valves and pumps. More details are given in [36, 39, 44].

4 Control and optimization of automotive fuel cell hybrid power systems

Owing to the structure and working principle of fuel cells, fuel cell control in automotive applications is a challenging but important problem in practice. Coordinating the crucial states and parameters, such as gas flows of hydrogen and oxygen and the temperature and humidity of the PEM, are essential in control system design. Moreover, the efficiency and lifetime of the fuel cell stack must be higher in FCV applications than in other applications and quick starts in cold environments are specially demanded in the FCV market. The following content surveys the control problems of fuel cell systems and their solutions.

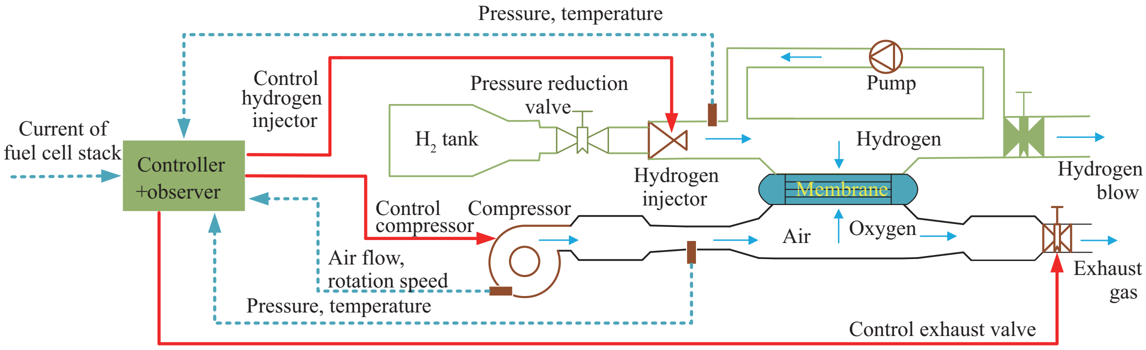

Figure 5 (Color online) Measurement and control of the air and hydrogen supply systems.

4.1 Control of air and hydrogen supply

The air and hydrogen supply systems, especially the air supply system, almost determine the dynamics of both the steady and transient power outputs. Therefore, air and hydrogen supply control should be first solved for generating electric power. However, the compact structure and distributed characteristics have resulted in insufficient state measurements in both the anode and cathode channels, thereby posing difficulties to the control problem.

Figure 5 displays the measurement and control of the air and hydrogen supply systems. Hydrogen pressure is the targeted adjustable variable in the anode channel, and the pressure and temperature can be measured at the anode-channel entrance of the fuel cell stack. Meanwhile, the concentration and partial pressure of oxygen in the cathode channel can be regulated by measuring the airflow into the compressor, rotation speed of the compressor, and pressure and temperature at the cathode-channel entrance of the fuel cell stack. For solving the control problem, the hydrogen pressure in the anode is regulated by a hydrogen injector, whereas the air mass flow and pressure in the cathode are usually controlled by coordinating the compressor and exhaust valve. As no pressure sensor or airflow sensor is installed in the cathode, observers are indispensable for estimating some states (e.g., partial pressures of hydrogen, oxygen, and nitrogen) in order to improve the control performances and accuracies of air and hydrogen supply.

Observer design is based on the model given by Eqs. (8) and (10) and on the partial pressure model of nitrogen and the compressor. The compressor speed, fuel cell current, and input and output pressures of the gas flow in the compressed air can be measured. The partial pressures or gas flows of hydrogen and oxygen in the anode and cathode channels, respectively, are then obtained by the designed observer. Initially, a linear observer based on a linearized model at the set point is designed using a Kalman filter and the linear-quadratic (LQ) Gaussian method [36, 45]. Later, because of the highly nonlinear property of the model, sliding mode technique and algebraic observer design approach are applied in [46–48]. The sliding-mode technique is also applied to fault reconstruction and power conversion of fuel cell systems [49–51]. We can reasonably assume that all states can be either measured or estimated by the observer. Therefore, air and hydrogen supply is usually controlled by a state feedback control strategy.

Controlling hydrogen pressure is easier than controlling air supply pressure because the channel is dead-ended and the hydrogen supply dynamics are fast and simple. The control problems associated with the hydrogen and water concentrations as well as hydrogen flow have been solved by nonlinear predictive control and fuzzy logic control approaches [52, 53]. The results show the effectiveness to control hydrogen concentration required for active current under load variation. Meanwhile, air supply control must not only guarantee accurate oxygen concentration for the reaction but should also couple with the humidity and temperature controls of the fuel cell stack. Therefore, air supply control is an essential requirement of fuel cell systems and has been actively researched in the past decades.

Researches on air supply control has usually focused on controlling the excess oxygen ratio, providing plentiful oxygen for the electrochemical reaction process, especially during abrupt changes in current load. During this time, the excess oxygen ratio needs rapid adjustment to prevent oxygen starvation.

This is achieved by increasing the air mass flow into the cathode channel. Most existing studies have assumed the steady point, with the humidity and temperature perfectly controlled at their optimal values. Related studies based on linear system control are abundant [45, 54–58]. Among the research results, Refs. [45, 54, 56] first proposed a widely used ninth-order model for airflow control. This model is used in the design of various feedforward, proportional-integral (PI), and LQ feedback controllers, which control the excess oxygen ratio. Furthermore, Ref. [56] first reduced the classic ninth-order model to a low-order nonlinear model and then proposed a methodology for tuning the gains of inner loop feedback linearization controller and the outer-loop PI controller. Their approach guarantees a stable control. A similar approach based on a reduced fourth-order model was investigated in [57]. They developed a control system for an air supply system using the linear parameter-varying approach and later presented a robust control for a compressor system [58].

The aforementioned controller designs and performance validations were achieved at limited set points and are not readily applicable over a wide range of operating conditions. In [59], a control strategy for the excess oxygen ratio was designed to overcome the oxygen starvation problem, but this strategy delivers slow performance due to nonlinearities. To improve this performance, Refs. [60, 61] applied a sliding-mode control for regulating the excess oxygen ratio over its operating range. The satisfactory performance of this control was confirmed in simulations and experiments. A previous research [62] accounted for the nonlinear characteristics of the system by collecting the required data and identified an appropriate model using recursive least-squares method, and then a fuzzy controller with a simplified rule was presented to cover most operating conditions. Refs. [63, 64] regulated the excess oxygen ratio during fast current transitions by employing a fuzzy PID controller design. In simulation tests, the fuzzy logic outperformed other control strategies in the automatic readjustment of controller parameters. A model predictive control (MPC) algorithm that incorporates the actuator limitations and state constraints in the control design has also been proposed [65–67]. MPC controls the air supply system by an optimal cost function that tracks the errors in the excess oxygen ratio, current load, and weighted inputs. Because solving nonlinear systems by MPC usually incurs a heavy calculation burden, the model is linearized at the given operating point. Linearization not only reduces the online optimal costs of optimization but also simplifies the controller design process. Fast algorithms based on the MPC framework, such as that proposed in [68], appear to be interesting and promising.

It is worth noting that though many studies have been done on air supply control, it is not well solved yet. Most studies on excess oxygen ratio control have been validated over a small range of operating conditions or the proposed method consumes excessive computational resources. An effective nonlinear control approach with reasonable computational complexity is still required. Furthermore, as the working pressure of a fuel cell system can reach 2.5 bar (1 bar is equal to 0.10108 MPa), both the excess oxygen ratio and gas pressures in the anode and cathode channels should be controlled simultaneously, which imposes further challenges. In contrast, improving the structure of the fuel cell system might enhance the potential and controllability of the dynamics and would pose new problems. If the humidifier is removed from the automotive fuel cell system, the air supply control can be highly coupled with humidification, power requirement, and probably temperature control. Thus, the excess oxygen ratio may not be the only target. Both the excess oxygen ratio and humidity must be regulated simultaneously [69]. As shown in [70], achieving fast airflow control in a pure fuel cell stack is limited by the minimum phase in the air supply system. However, if ESS is available in the power system and compressor is powered by an additional battery package, the minimum phase problem can be eliminated. In this case, the application of control theory to fuel cell systems might be a fruitful avenue of future research [56]. Besides the compressor, which controls the air supply control, a power split strategy can greatly improve the control of the transient excess oxygen ratio [71, 72]. In an improved power system, the new control problem involves optimizing the desired cost function while regulating the air supply.

4.2 Humidity control

Humidity control, which maintains proper hydration of the polymer membrane, is a difficult problem in practice [73]. Low humidification levels must be avoided as they severely affect the electrode kinetics in the stack and reduce the lifetime. Excessive water should also be avoided because high humidity levels cause liquid water accumulation in the channels, degrading the system efficiency and reactant utilization. As shown in [74], the ideal relative humidity (right below 100% across the entire fuel cell stack) optimizes the system efficiency, minimizes membrane damage, and avoids membrane flooding. To maintain saturated conditions, the relative humidity is usually held between 80% and 100% [75].

Humidity control is very important, if not vital, for the long life and efficiency of the fuel cell stack but remains a challenging and open issue. Humidity control performance is determined by multiple factors, including temperature, electrochemical reactions, mass transport in the channels, and geometric structure of the stack. The humidity model in Subsection 3.4 is valid provided that all generated water is in the vapor form and that the channels are free of liquid water. This assumption is quite critical but reasonable under narrow operating conditions. Once the liquid water has been generated for fast electrochemical or low-temperature reactions, proper humidity control is necessary for avoiding the flooding phenomenon. Moreover, liquid water in the stack cannot be detected directly although the humidity of the output gas flow can be measured by sensors. Ref. [76] proposed a water management strategy to avoid flooding and dehydration by controlling the hydrogen pressure drop. If such water faults can be diagnosed through the pressure drop, as reviewed in [77], humidity control can assume a single-phase water flow.

Because the water concentration in the membrane cannot be measured directly but is determined by the relative humidity of the anode and cathode sides, humidity control regulates the relative humidity in the anode and cathode channels. In this case, the water inside the membrane is controlled indirectly. In the literature, the humidity of the fuel stack is controlled using two methods. One method uses additional humidifier equipment or accessories to control the humidity of the inlet gases [78–81]. The other method employs self-humidity technology that regulates the water generated by the electrochemical reaction [82].

External humidification is a direct and flexible water management approach for controlling the relative humidity of inlet gases. Figure 1 shows the typical structure of a fuel cell with additional humidifiers along the hydrogen and air paths. This approach regulates the gas humidity in the anode and cathode channels, which in turn controls the water concentration in the membrane. Ref. [81] systematically discussed the effect of humidifying the anode and cathode inlets on the fuel cell performance. The influences of the humidified inlets are typically asymmetrical but together determine the maximum power density of the fuel cell. Ref. [79] regulated the humidification rates of the air and hydrogen gases under constraints that avoid dehydration and flooding. In simulation tests, the regulation significantly improved the fuel cell efficiency (by up to 20%). When the humidifier is installed in the fuel cell stack, most discussions of humidification control excessively simplify the dynamics in the fuel cell. For example, humidifier modeling and control are studied in [44], whereas the modeling and control of cathode air humidification is discussed in [78]. Both studies [44, 78] focused on the humidifier itself, with little discussion of the humidity dynamics in the fuel cell stack. In [80], a nonlinear model predictive controller was proposed to control the humidity and pressure of the anode. Their system considers auxiliaries, e.g., humidifiers, manifolds, and line heaters. However, because it oversimplifies the dynamics of the electrochemical reaction, it hardly resolves the main problem, i.e., humidity regulation of the fuel cell.

When the humidifier is removed, the water concentration should be regulated by controlling the gas flow and temperature, which apparently couples to other loops. In a miniature fuel cell system, the oxygen excess ratio, membrane humidity, and stack temperature are controlled by a fan that controls the airflow. In [75], the influences of the inlet humidity, inlet temperature, and power demand on the water concentration in the membrane are discussed and an open-loop airflow controller is designed to maintain a constant outlet humidity under saturated conditions. In [83], a miniature PEMFC was controlled by a fuzzy logic approach. Unlike other studies, their approach uses the impedance of the fuel cell stack and the minimum cell voltage as feedback signals that indirectly indicate the water balance in the membrane. This method is suitable when the power demand is constant but is inapplicable under varying power operating conditions when the impedance and cell voltage are constantly varying. Ref. [84] managed both the heat and water in a miniature fuel cell by a phase portrait analysis and tested its performance via simulations. A gain-scheduled static feedback controller, which regulates the humidity and anode pressure by an ejector-based anode recirculation loop, is discussed in [85]. The results concluded that the

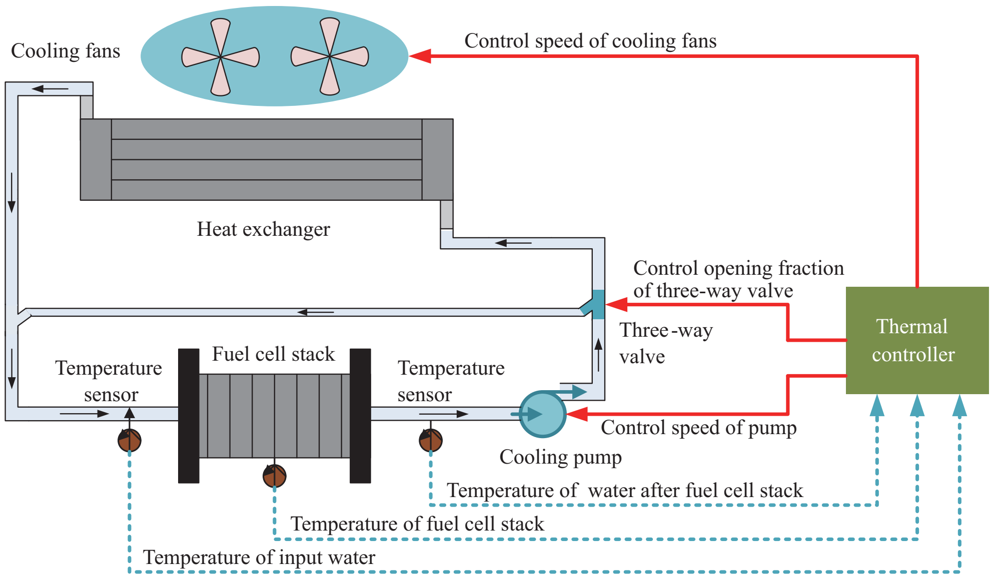

Figure 6 (Color online) Measurement and control of temperature using a water cooling system.

cathode water activity must be measured in the presence of liquid water and that fast humidity sensors are essential for achieving the desired performance. Ref. [82] proposed two types of exhaust gas recirculation systems for controlling cathode humidification. They experimentally demonstrated that their systems are viable alternatives to the conventional humidification system; however, developing them to their full potential requires additional effort.

Overall, one can easily appreciate that controlling humidity in an automotive fuel cell is much more challenging and important than controlling air and hydrogen supply. An even worse situation is that the fuel cell stack in automotive applications is more complicated and much larger than the miniature version. Ensuring uniform operation of each cell under the nonuniform distributions of oxygen, humidity, and temperature is particularly difficult. Refs. [73, 74] proposed a multiple volume control model and a methodology for controlling humidity in nonuniform volumes. Ref. [86] presented a distributed parameter model of the through-plane water distributions in PEMFC. When applied to humidity control in FCVs, this complicated model will result in additional difficulties. Moreover, as a real-time, non-intrusive measurement technology for in-cell humidity is lacking [75], the robustness of humidity control to model mismatch and disturbance is not guaranteed. Humidity estimation based on indirect measurements, e.g., hydrogen pressure drop, dynamic impedance, and cell voltage, might improve the current control performance but requires further investigation.

4.3 Temperature control

As clarified in the electrochemical reaction model in Subsection 3.1, the temperature of the fuel cell stack directly determines the ohmic loss in the fuel cell and indirectly influences the membrane humidity by controlling the saturated humidity of the gases in both the anode and cathode channels. Compared with ICE system, a fuel cell system demands a much stricter heat-exchange system with higher control precision. To guarantee high efficiency and long lifetime of the proton membrane, the temperature of the fuel cell stack should be controlled at 80°C and homogenized over its length.

The temperature in a cooling system can be controlled by either an air fan or a water cooling system. In practice, air cooling systems (which have small heat-transfer capacity) are limited to low-power fuel cell stacks (below 10 kW), whereas water cooling systems are usually installed in high-power fuel cell systems. The measurement and control of temperature using a water cooling system is presented in Figure 6. The temperature of the fuel cell stack and of the water flows before and after the fuel cell stack can be measured using sensors. Three kinds of actuators are usually available for temperature control: a cooling pump, a three-way valve, and a heat exchanger containing a radiator and cooling fans.

Usually, only parts of the actuators in Figure 6 are used for temperature control and a lumped-parameter dynamics model is used for controller synthesis. Ref. [87] proposed a first-order nonlinear model that captures the thermal dynamics of a PEM fuel cell stack by controlling the coolant flow rate. The controller regards the temperature variation of the input coolant flow as a measurable disturbance while the control problem of cooling system is not mentioned. A time-varying PI controller similarly controls the temperature of a 5-kW fuel cell stack by adjusting the coolant flow rate [87, 88]. A cooling system containing a radiator and a fan was considered in [89] for controlling the temperature of the fuel cell stack. In that study, the fan speed was regulated by a PID controller in a first-order linear time-invariant system, while the coolant mass flow was controlled according to the load. However, the model strategy was not discussed in that paper. Ref. [90] considered the stack temperature and cooling water temperature as state variables and proposed a robust adaptive controller based on the backstepping method to deal with unknown parameters and disturbances. Simulations confirmed the obvious superiority of the robust controller over traditional PID control. Ref. [91] investigated the temperature regulation of a PEM fuel cell system installed on a bus. Their method processes the delay caused by the stack-to-radiator water flow via Pade approximation. Then, a linear quadratic regulator (LQR) method for the current duty cycle of the cooling fan was designed based on the linearized model in the neighborhood of the nominal operating point. Ref. [92] regulated the coolant water flow by an active disturbance rejection control. The high-gain observer and controller in their design method theoretically ensures good performance, but the method suffers from the system delay, as mentioned in [91].

The above studies considered only one type of actuator (either a cooling pump or a cooling fan). More actuators would greatly benefit the temperature performance. In [93], three types of controllers were designed to analyze the effect of pumps and radiator fans on temperature regulation. The advantages of using pumps and fans as control variables were well clarified. The study recommended the design of closed-loop pump control with less use of the fans because fans induce more parasitic power loss than pumps). Regarding both coolant flow and three-way valve fraction as inputs, Ref. [94] linearized model near equilibrium by Taylor's expansion, and controlled the stack temperature using an LQR method with a minimal cost function. Ref. [95] provided a reference adaptive control algorithm to achieve robust temperature regulation. As the temperature of the fuel cell stack can be adjusted by both the coolant flow and three-way valve fraction, the proposed strategy can potentially be further optimized. Considering a thermal management system same as that proposed in [94, 95], a PI and an LQR controller were designed and compared in [96]. Compared with the PI controller, the LQR controller delivered a better dynamic response with lower parasitic loss. Ref. [97] designed an MPC controller that minimizes the temperature deviation from the reference while constraining the radiator fan control and current load. As demonstrated in simulations, the MPC limited the current load when the thermal management system reached its maximal cooling capacity, guaranteeing the lifetime and performance of the fuel cell.

Instead of a lumped-parameter model, Ref. [43] proposed a variable structure control strategy based on a complicated 16th-order model, which controls the fuel gas and cooling water exit temperatures as well as the bipolar plate temperature in the cathode of the stack. The controller parameters were further optimized by a genetic algorithm [98] that tunes the thermal model-oriented control law. The overall effectiveness of the strategy was validated via a numerical test. As an alternative to the above water and air cooling systems, Ref. [99] proposed an evaporative cooling system and simulated it in a PI controller corresponding to the given model. The cooling system delivered a better temperature control performance, faster warm-up, and less heat loss at low operating load than the water cooling system. Ref. [100] proposed a thermal control scheme with separate circuits for heating and cooling. This scheme prevents the stack from overheating under a high external load and from remaining too cold in low-temperature environments. The effectiveness of the system was validated using a logic control strategy. Because the proposed thermal management system comprises five actuators, i.e., two fans, one coolant heater, one coolant pump, and one thermostat, quantitatively allocating the control variables is a challenging and interesting task.

Summarizing the temperature control of the automotive fuel cell stack, it can be seen that the mechanical structure of the measurement and control system closely matches that of a conventional ICE and

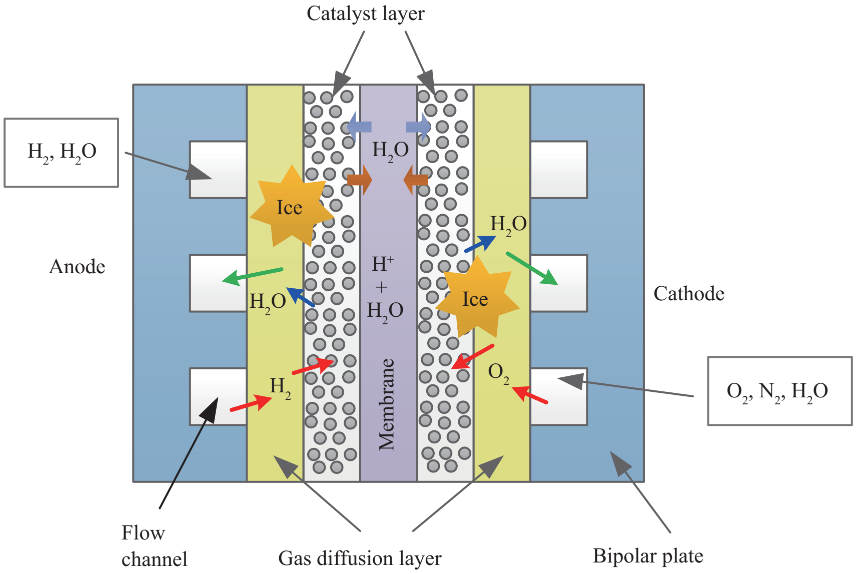

Figure 7 (Color online) Material transport in a fuel cell at cold start.

that the maximal cooling capacity requires 1.2 times the rated power of the fuel cell system. Therefore, an automotive fuel cell stack not only demands a large cooling capacity but also requires a more precise control (because of the narrow working range) compared with the conventional ICE. To this end, a feed-forward compensation for the heat power generated by the fuel cell stack plus a feedback correction of the temperature-tracking error seems necessary. Therefore, a high-fidelity model of the thermal system is required. Moreover, the cooling fan of the fuel cell stack is driven by high-voltage electronics, which increase the parasitic power loss. Hence, the power consumption of the thermal management should also be optimized when controlling the temperature of the fuel cell stack.

4.4 Cold-start control

The cold start control starts the fuel cell stack under subfreezing conditions or prevent the temperature of the fuel cell stack from decreasing below 0°C. This ensures that the stack restarts normally in a sub-zero environment. Therefore, the cold start control mainly focuses on the start-up process of the fuel cell at sub-zero temperatures or when the stack must remain in a cold environment for a long period. This problem has greatly hindered the mass application of PEMFC vehicles because automobiles must operate well under extreme conditions. For instance, the temperature can reach 40°C or even 50 °C in some regions or can drop below −30 °C in cold northern regions. Subsection 4.3 discussed the cooling methods that limit the maximum temperature of the stack. In contrast, this subsection summarizes the efforts and strategies for warming the stack within a short period or maintaining it below its desired temperature.

The cold start control has two objectives. First, the stack must start within a limited time. In 2020, an FCV is projected to output 50% of its rated power within 30 s at −20°C [101]. Second, the cold start control must protect the stack from ice formation and freeze/thaw cycling, which irreversibly degrade the cell and its performance. Figure 7 shows the material transport in the fuel cell at cold start. Humidified hydrogen and fresh air are supplied from the flow channel of the anode and cathode, respectively, and form water by a reduction-oxidation reaction. If the temperature remains below 0°C after water saturation of the membrane and catalyst layer, ice formation will prevent the occurrence of the electrochemical reaction and permanent damage to the stack. However, when liquid water begins accumulating in the gas diffusion and catalyst layers at ambient temperatures above 0°C, the cold start is successfully completed. Therefore, as mentioned in [102], a successful cold start requires a delicate balance between water and heat generation.

An initially dry membrane benefits the cold start process not only by increasing the saturation potentials of the membrane and catalyst layers but also by increasing the time to remove water from the stack [102, 103]. Thus, gas purge after shutdown is an essential process for the cold start operation. Ref. [104] experimentally validated that the preferred purge duration preserves the cell performance after freeze/thaw cycles. They also established that the anode requires no purging under certain conditions, which is greatly desired in automotive applications. Ref. [105] explored gas purging of a PEMFC stack and determined the optimal purge duration with dry gas as 120 s. They emphasized that the cold start performance strongly depends on the purge time and start-up temperature. A similar purge time was experimentally obtained in [106].

Besides the gas-purging of water, thermal management is vital for cold start. In a summary of patents and published articles, Ref. [107] identified two thermal management strategies of cold starts: the keep-warm method and the thawing/heating method. The keep-warm method prevents the stack from freezing, preventing possible damages caused by ice formation and freeze/thaw cycles. A keep-warm device for fuel cell buses [108] maintains the fuel cell within a certain temperature range, ensuring a fast start-up system. Ref. [109] patented a thermal control system that keeps the fuel cell warm for a long time after shutdown. This system comprises a heating system and an insulated fuel cell system, both of which minimize the thermal losses via insulation technology and generate additional heat energy for rapidly warming the stack. Thus, when applying keep-warm method, grid connection or battery with large energy capacity is necessary and should be available in the automotive system.

Thawing/heating methods enable fast start-up of the fuel cell stack, which requires a high-power resource. These methods warm the fuel cell stack after a successful start-up and gas purge, even at very low environmental temperatures. Self-start-up has been the main solution in thawing/heating methods. A constant-current cold start approach warms the fuel cell from -10°C [110]. In that study, the fuel cell was operated in constant-current mode. A lower start-up current failed to increase the water storage capacity of the fuel cell but generated sufficient heat to warm the stack and reduce ice formations. However, this approach extends the time of a successful cold start. Ref. [111] controlled the current density in a rapid start-up strategy. They reported that raising the current in the under saturated stage is very effective and significantly improves the cold start behavior by shortening the start-up time. Ref. [112] studied the effect of current density on a printed circuit board. They showed that increasing the initial load and setup temperature reduces the cold start time. Nevertheless, the warm-up period from -20°C was 20 min, far from the demanded cold start in automotive applications. A constant voltage strategy has also been proposed, and its performance was compared with that of the constant-current cold start approach [113]. In fact, all self-start-up strategies increase heat generation by reducing the fuel efficiency and avoiding ice formation.

A fast and successful start-up process requires both high self-start-up performance and a capable supply of external heat. To improve the cold start performance, Ref. [114] proposed variable heating and load control for efficiently utilizes the external heating power and the self-heating ability of the stack. Ref. [115] exploited the advantages of both the external and self-heating systems in a global cold start strategy for hybrid FCVs. They developed a time-optimized bang-bang self-heating rule based on the Pontryagin minimum principle and implemented it in the supervisory architecture of an energy management system. However, the proposed strategy divides the cold start process into two stages: the battery-powered heating stage and the self-heated warm-up stage. These two heating methods are implemented separately. Other cold start solutions, such as anti-freezing materials, warming mechanisms, and control and sensing systems, are reviewed in [116].

4.5 System optimization and energy management

4.5.1 *System optimization*

The aforementioned topics covered various control issues associated with automotive fuel cell systems. All these problems must be solved for mass application of electric vehicles. Meanwhile, coordinating many parameters and states of a fuel cell will significantly improve the efficiency and lifetime of the fuel cell. Ref. [117] revealed that the efficiency of a PEM fuel cell largely depends on the voltage, pressure, and purge

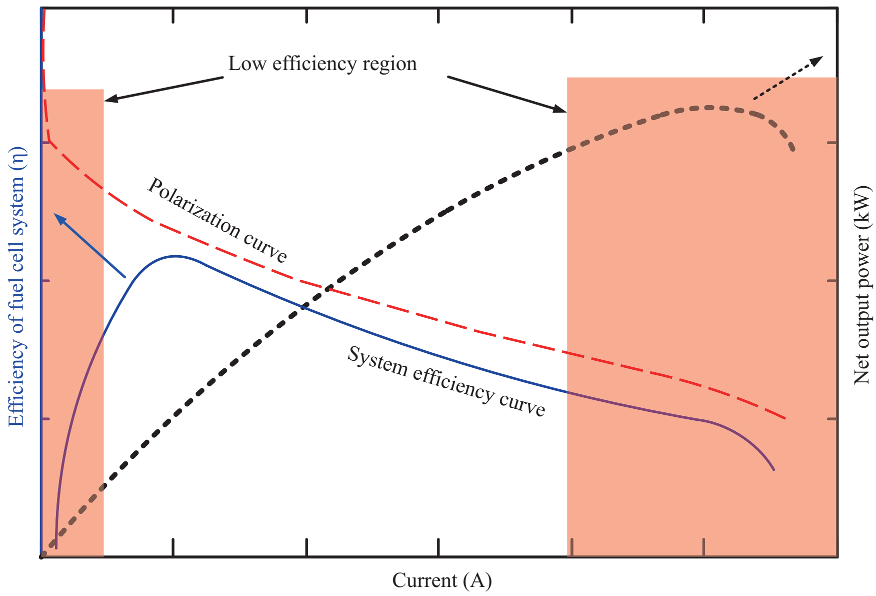

Figure 8 (Color online) Efficiency and net output power as functions of load current in a fuel cell system.

processes and that parameter optimization can improve the cell performance. Refs. [118, 119] optimized the air and fuel flows by optimizing the mixed net power and fuel consumption efficiency of the fuel cell. To solve this multi-optimization problem, they applied a method that seeks the global extremum. The energy efficiency of a system controlled by the optimization method was improved by 1.0%–2.1%. A model based on neural networks and semi-empirical equations captures the influence of the control parameters on the system efficiency [120]. This model, which optimizes the operating conditions, improved the efficiency by 1.2% and 5.5% under the worst and best testing operating conditions, respectively. By similar procedures, Ref. [121] optimized the operating condition by varying the back pressure and Ref. [122] established a maximum performance polarization curve at each current intensity.

Unlike the traditional ICE, fuel cell systems have several characteristics that limit their applicability as the sole power source in automobiles. First, the dynamics of fuel cell systems are slower than the power changes demanded by drivers. Second, the efficiency of fuel cell systems is relatively low and not competitive with other type of powertrains under some operating conditions. The efficiency is degraded by parasitic loss, activation loss, and concentration loss, as discussed in Subsection 3.1. Figure 8 presents the efficiency and net output power of a fuel cell system. The polarization curve is mainly determined by the electrochemical reaction and the three types of losses in the fuel cell system. As the load current is increased, the net output power of the fuel cell system (black dotted line in Figure 8) first increases and later decreases because of the inefficient electrochemical reaction. Under a low load current, the electrochemical reaction is highly efficient, but the system efficiency is much reduced by parasitic losses from the air compressor, hydrogen recirculation pump, and other components. Therefore, the system efficiency increases up to the load current, which significantly compromises the electrochemical reaction. A fuel cell system should simultaneously avoid both low-load and high-load operating conditions.

Hybrid FCVs are among the most promising fuel cell solutions for automotive applications. As shown in Figure 3, an FCV requires an ESS with a battery and/or an ultra-capacitor. Ref. [19] reviewed the structures of hybrid FCVs and identified six main topologies in past proposals. Ref. [123] investigated various topologies and emphasized that single devices, e.g., batteries, ultra-capacitors, and fuel cells, cannot meet all requirements of automotive vehicles. Refs. [124, 125] investigated how second-source technologies can benefit the performances of FCVs. They showed that a system with a high hybridization ratio lowers the fuel consumption and weight of the vehicle and extends its lifetime, but the benefits highly depend on the energy management strategy.

Three improvements remain in the optimization of hybrid power systems for automotive fuel cells. The first is the development of the fuel cell system. Although the main technical targets, e.g., peak energy efficiency, power density, and specific power, have met the technical targets of DoE, the durability (average state-of-the-art durability status measured in the laboratory) was only approximately 3700 h in 2017). Cost remains a major challenge in the commercialization of fuel cells [126]. The development and optimization of PEMFC components and auxiliaries (humidifier and air compression system) also need further improvement. The second problem is optimizing the control system of automotive fuel cells. High performance and efficiency can be ensured only by tightly coordinating the parameters of excess oxygen ratio, pressure, temperature, and humidity. Single variable control has yielded fruitful results, but variable coordination under different operating conditions requires thorough investigation. The third problem is parameter optimization of the power system in automotive hybrid fuel cells. The effects of the hybridization ratio and ESS type on the system performance must be determined in quantitative analyses.

4.5.2 *Energy management*

An energy management strategy of hybrid FCVs should distribute the desired load to the energy system, including the fuel cell system and ESS, such that the desired power is satisfied, the system lifetime is ensured, and the efficiency is optimized at the same time. To optimize the efficiency of a fuel cell system, Ref. [127] considered an online extremum-seeking method that finds the optimal operating point. The lifetime of the energy system is assured via dynamic classification that distributes the global power mission of the vehicle [128]. Here, the ultra-capacity system, the battery, and the fuel cell system were classified as the highest, intermediate, and lowest dynamic power sources, respectively. Similar to [128], dynamic classification rules based on the wavelet transform were presented in [129]. They generated reference power signals and refined the power distribution using a fuzzy logic method. However, a satisfactory energy management strategy must simultaneously solve multiple objectives. Most results published in the past few decades can be categorized into two types of energy management strategies: rule-based methods and optimization-based methods.

As discussed in [130], rule-based methods rely on engineering knowledge, intuition, and pre-defined driving cycles on the vehicle. They are generally divisible into deterministic and fuzzy rule-based methods. The typical input variables are the desired power, state of charge (SOC) of the ESS, efficiency and dynamic limitation of the fuel cell, and driving modes. Ref. [131] proposed two deterministic rule-based strategies, each governed by dynamic classification rules that guarantee the battery lifetime. A voltage control function of the ultra-capacitor proposed in [132] maintains the SOC between the defined lower and higher limits. Ref. [133] divided the operating conditions into traction, braking, and stopping modes, and provided tables of deterministic rules that account for the SOC limitation of the battery. Although these studies consider the lifetime of the hybrid energy system, they ignore the efficiency of the fuel cell system. Fuzzy logic controls are widely applied in the energy management of hybrid FCVs. Refs. [134, 135] separated several modes according to the SOC of an ESS and designed a fuzzy logic for a demand-based power distribution to the SOC of the ESS, the DC/DC power, and the fuel cell. Based on online pattern classification of driving cycles using a probabilistic support vector machine, Ref. [136] fused optimized fuzzy logic controllers and applied them to the classification of real online driving cycles. Ref. [137] proposed an ON-OFF strategy for fuel cell extended-range vehicles and designed a fuzzy logic control strategy for power following when the fuel cell is ON. To avoid the load variation and mode switching effects caused by logic shifts, Refs. [138, 139] implemented fuzzy logic in a flatness control technique. Rule-based methods negate the need for an accurate system model, and the performance can be near-optimized by adjusting the parameters. Unfortunately, the controller parameters should be repeatedly adjusted based on experiments and/or simulations, which is sometimes time-consuming and largely dependent on engineering skills to obtain an acceptable performance.

In contrast, optimization-based methods usually require an accurate model or numerical operations to minimize the cost function. By employing an optimal theory or algorithm, an optimization-based method supplies a solution with the best performance indicator. Ref. [140] proposed the most reasonable equivalent consumption minimization strategy (ECMS) based on a local optimization method, which near-optimizes the performance without any a priori information. Ref. [141] improved the ECMS by adding a dynamic factor that maintains the SOC of the battery. They also proposed a self-adaption function that enhances the efficiency of the hybrid energy system. When employing a global optimization method, the information of the short term or whole trip should be known a priori or forecasted online, which is a major barrier to real-time control. Ref. [142] designed a minimum fuel consumption strategy based on Pontryagin's minimum principle and forecasted the total trip length based on the past information of driving cycle speed. Their algorithm includes an optimal energy management strategy for fuel cell/ultra-capacitor hybrid vehicles, which estimates the short-term energy demand while constraining the slow dynamics of the fuel cell and the SOC of the ultra-capacitor. As another optimization solution, Ref. [143] predicted the long-term information and the short-term speed using k-nearest neighbor classification and a model averaging method, respectively. Next, they determined the global optimum using a hierarchical reinforcement learning method. The energy optimization method proposed in [144] exploits the advantages of the MPC approach. The power demand is predicted by Markov chains and neural networks. When the mission profile is known or estimated beforehand, the global optimal solution can potentially optimize the vehicle control strategy [145]. Ref. [146] proposed an offline optimization strategy for fuel consumption under all constraints of the system (i.e., power demand, power output capability of the fuel cell, and SOC of the ultra-capacitor). Ref. [147] modeled the power demand of the whole trip by a Markov decision process and obtained an optimal strategy by stochastic dynamic programming. Ref. [148] first obtained a control series of optimal energy consumption in different types of driving cycles and then trained a neural network controller on the optimal power distribution series. Because optimization-based methods are derived from model dynamics analyses and numerical iterations, their performances are ensured only when the system model has been accurately obtained.

In real applications, the control unit is computationally limited by cost constraints and by the precision of the system model and trip prediction. Therefore, determining the best strategy under all operating conditions is difficult. Ref. [149] compared the performances of two rule-based methods and one optimization-based method. Although the performances of the three methods were similar, the rule-based methods largely conserved the computational resources. However, the proposed optimal strategy needs the entire driving cycle information in advance, which is not feasible in practice. Ref. [150] compared the performances of ECMS and three rule-based methods. The methods yielded similar results in almost all energy management strategies investigated herein although ECMS was apparently the most preferred control strategy. Ref. [151] optimized the energy management strategy over a combined driving cycle by a two-step process: fuzzy logic in the first step and adjustment of the control parameters by multi-objective optimization in the second step. In the simulation results, the fuel economy, vehicle performance, and battery charge-sustaining capability were enhanced. Ref. [152] designed an ON-OFF logic for a fuel cell extender and optimized the fuel consumption by a genetic algorithm when the fuel cell extender is ON. This combined switching control strategy by a genetic algorithm, increased the driving range. These preliminary studies confirm the feasibility and effectiveness of mixed methods combining rules with optimization algorithms. Nevertheless, to optimize the energy management at affordable computational complexity, further research on the technical details, e.g., correct design rules and tune their parameters for the optimization results is required.

5 Conclusion

Hydrogen energy is probably regarded as the ultimate replacement fuel of present fossil resources in current transportation systems. Hydrogen gas has a high energy density and can be generated by many clean routines to satisfy the burgeoning demand for transport fuels in the future. Therefore, the main countries worldwide are competing in the race for alternative energy developments and advanced automotive manufacturers have already begun releasing commercial FCV productions. However, the cost of fuel cell systems remains prohibitively high for the mass production of FCVs. Moreover, the corresponding infrastructure, e.g., hydrogen plants and filling stations, is still far behind the requirements if FCVs are to replace traditional ICE-based vehicles.

After a further decade of research on PEMFC systems and the applications, developments, and improvements of automotive fuel cell systems, PEMFCs will likely compete with ICE. An automotive fuel cell system with adequate performance must operate over a long duration with high efficiency and reliability at low cost and with a long lifetime. To achieve these targets, the material of the membrane electrode assembly must be improved, along with the control technology that regulates the system states. The parameters that influence the system efficiency must be fully analyzed, and the system efficiency must be optimized.

By investigating the fuel cell systems designed by advanced automotive manufacturers, one can observe the trend toward the format of traditional ICE, which integrates the fuel cell stack and its accessories, the driving motor and its controller, and the cooling and control systems as a powertrain unit. This kind of structure can directly replace the current powertrain system, but its compact size narrows the temperature difference between input and output water flows of the cooling system, which greatly challenges the temperature control. Moreover, the automotive application demands a cold start capability of the fuel cell system because the operating conditions of vehicles are diverse and sometimes harsh. To date, cold start remains a challenging problem in fuel cell control.

Furthermore, the power requirements of a vehicle contradict the low transient dynamics of a pure fuel cell system. To compensate for this drawback, researchers have developed hybrid energy systems combining the fuel cells, batteries, and/or ultra-capacitors. These systems have become acceptable choices in applications. The system efficiency with an acceptable lifetime has been optimized in various combinations and topologies, but the best strategy should consider both cost and performance. Therefore, the best general strategy is inconclusive. The corresponding energy management strategy has been widely implemented by rule- and optimization-based methods, which have been validated via simulations and/or experiments. Mixed methods combining both strategies are emerging as a promising solution.

Acknowledgements This work was supported by National Key Research and Development Program of China (Grant Nos. 2017YFB0102800, 2018YFB0105300) and National Natural Science Foundation of China (Nos. 61703179, 61703177).

Supporting information Appendix A. The supporting information is available online at info.scichina.com and link.springer.com. The supporting materials are published as submitted, without typesetting or editing. The responsibility for scientific accuracy and content remains entirely with the authors.

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