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Anode flooding characteristics as design boundary for a hydrogen supply system for automotive polymer electrolyte membrane fuel cells

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HIGHLIGHTS

- The critical Reynolds number for water removal from a PEM fuel cell anode is obtained.
- Various automotive hydrogen supply systems are compared with the resulting requirements.
- Only active recirculation systems achieve the requirements for all fuel cell load points.
- Passive systems require a hybridization strategy of the fuel cell system.

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ABSTRACT

An automotive fuel cell is investigated to define the design boundaries for an automotive hydrogen supply system with regard to anode flooding. The flooding characteristics of the fuel cell anode at various operating conditions (hydrogen flow rate, pressure, temperature, current density) are analyzed by in-situ and ex-situ measurements. Stable operation conditions are identified and a relation to the operating conditions is established. For adequate water removal, a minimum Reynolds number in the gas channels has to be adjusted. Using this information, different hydrogen supply system designs are compared in their compliance with the stability requirements. It is shown that passive hydrogen supply systems do not achieve all fuel cell requirements regarding power density, lifetime and robustness.

1. Introduction

Electric vehicles powered by fuel cell systems offer high driving ranges with low refueling times. For customer acceptance, the lifetime and reliability of an automotive fuel cell system should be equal or exceed the standards of an internal combustion engine. The U.S. Department of Energy [1] has set a target for the year 2017 for mobile fuel cell systems to reach a lifetime of 5000 h at the costs of 30 US $ per kW. This implies for example that a fuel cell vehicle with this lifetime can drive an overall distance of 250,000 km at an average speed of 50 km per hour. The end of lifetime (EOL) for a fuel cell system can be defined by the voltage degradation of the fuel cell stack, which is in reference to the beginning of life (BOL) voltage. The U.S. Department of Energy sets the voltage degradation at EOL to 10% of the BOL voltage at rated power output. Among other degradation mechanisms that cause voltage degradation, fuel starvation leads to a significant catalyst degradation [2]. Fuel starvation scenarios occur during freeze starts, air–air starts and poor water management.

Water management is important for polymer electrolyte membrane (PEM) fuel cells. The correlation between humidity of the membrane and proton conductivity requires high humidity levels in the membrane to reach the best performance of a PEM fuel cell system. High power densities are essential for integration of a fuel cell system in a vehicle because of the limited space available. As a consequence thin membranes are used and supplied reactant gases are humidified to achieve high membrane humidity levels. Water transport mechanisms in the membrane like electro-osmotic drag and water diffusion lead to a continuous change of water concentration along the gas channels of the anode and cathode. Due to reaction on both electrodes of the fuel cell and low

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temperature operation, water vapor can condense and water droplets block the gas supply to the electrodes. While air starvation is not critical for the lifetime on the cathode side, fuel starvation on the anode side can lead to oxidation of the carbon support of the cathode [2,16]. The oxidized carbon is washed out of the fuel cell, and the fuel cell is irreversible damaged.

1.1. Automotive hydrogen supply system layouts

The task of an automotive hydrogen supply system is to prevent fuel starvation and keep the membrane at high humidity level with few, economic and robust system components. The membrane humidity level is also influenced by the air supply system. To prevent fuel starvation on the anode side, water accumulation in the gas distribution channels must be avoided and liquid droplets have to be removed until a maximum tolerable amount of liquid water in the gas channel is reached.

A simple layout for a hydrogen supply system is the dead-end design (Fig. 1A), where hydrogen is fed from a storage tank by a pressure controller to the fuel cell. Water droplets in the gas channels and nitrogen, which diffuses through the membrane from the cathode side, are periodically removed by a purge valve. The opening of the purge valve induces a pressure drop over the fuel cell that forces liquid water droplets to movement. A challenge for this design is the equal distribution of hydrogen to all cells in the stack, which is related to the flow characteristics and the manufacturing quality.

Chikugo et al. [3] investigated a dead-ended fuel cell system for automotive applications. They used a buffer tank between the anode exhaust and the purge valve. For adequate water removal the hydrogen stream to the fuel cell was pulsed by the pressure controller. These pressure pulses force liquid water and nitrogen into the buffer tank, which is drained regularly.

Another operation mode to remove liquid water and nitrogen is to increase the velocity of the hydrogen flow in the gas channels. In this case, the continuous flow through the fuel cell needs to be sufficiently high to overcome the viscous forces of the water droplets. This operation mode leads to high fuel losses if the exhaust is not recycled. To prevent this, recycling of the exhaust gases is arranged by passing the gases back to the inlet of the fuel cell (Fig. 1B).

The advantage of this kind of system layout is that water vapor and nitrogen gas can be recycled. Recycled water vapor can be used to omit a hydrogen humidifier at the fuel cell inlet, and the nitrogen gas increases the flow rate to remove water droplets.

A challenge in recycling the exhaust gases is the higher gas pressure level at the inlet of the fuel cell compared to the outlet pressure. To overcome the pressure difference, a recirculation pump is needed. Hydrogen recirculation pumps can be divided in two groups: Active pumps that need an electrical power source for operation, and passive pumps working with fluid energy without electrical power consumption.

Different types of fluid flow engines are used for active recirculation. The fluid flow engines need to be compatible to hydrogen and water vapor mixtures. For this reason, regenerative blowers or roots compressors are used in vehicular fuel cell systems [4,5].

Fluid energy pumps work with the principal of momentum transfer from the intake gas to the recirculated gas and need no electrical power supply. They are thus passive recirculation devices. The gas velocity of the intake gas is increased in an orifice to produce low-pressure to suck in the exhaust gas of the fuel cell. These pumps are simple, low cost and maintenance free, but they only function if an intake stream is present [6].

Dehn et al. [7] proposed a near-dead-end hydrogen system with a cascaded fuel cell stack with continuous hydrogen flow. In their concept (Fig. 1C), the fuel cell stack is divided into four anode stages, where the exhaust gas of one stage is the inlet gas of the next stage. The advantage of this near-dead-end design is that each stage gets the hydrogen stream from the following stages, only a small part of the overall supplied hydrogen is exhausted through a

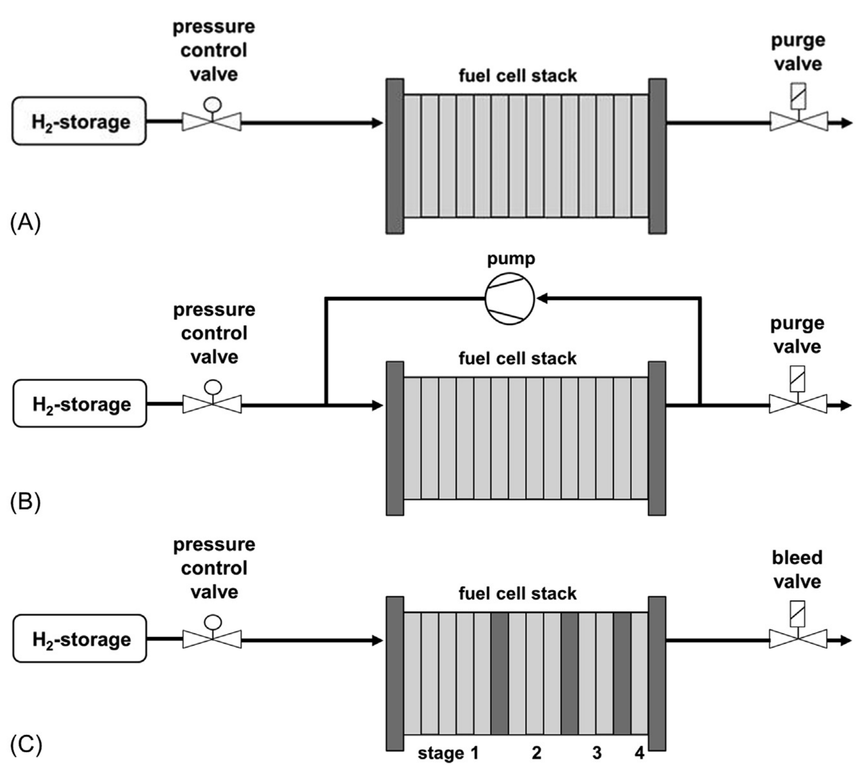

Fig. 1. Hydrogen supply systems: (A) dead-end stack and purge valve; (B) active recirculation and purge valve; (C) cascaded stack on anode side and bleed valve.