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Reactant recirculation system utilizing pressure swing for proton exchange membrane fuel cell

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ABSTRACT

To minimize the wastage of supplied reactant, fuel cells need to be operated in either dead-end or recirculation modes. A fuel cell operating in a dead-end mode is not durable without periodic purging because of flooding; therefore, a little reactant is unavoidably wasted. Conventional recirculation systems employ mechanical pumps or ejectors as their recirculation devices, but they have drawbacks originating from the inherent properties of pumps and ejectors. This paper proposes a pumpless reactant recirculation system, the pressure swing recirculation system, which utilizes pressure swings produced by the reactant supply and consumption. This system requires only two check valves and a fluid control device, and operates by alternating between the equivalent flow-through and dead-end modes. The proposed system was applied for both anode and cathode of a PEMFC. A single cell was operated in dead-end and pressure swing recirculation modes for comparative analyses. The resultant cell performances in the dead-end mode deteriorated rapidly because of flooding, while those in the pressure swing recirculation using high-purity reactants were stable and durable over 10 h. The experimental results demonstrated that the pressure swing operation could expel the product water from the cell, and operations over 10 h were achievable as long as the purity of the supplied reactants was high enough.

1. Introduction

Fuel cell technologies, such as proton exchange membrane fuel cells (PEMFCs), direct methanol fuel cells, and solid oxide fuel cells, have been attracting attention as concerns about global warming and demands for high-energy power sources have increased. In particular, PEMFCs have been extensively studied and are still under intensive research and development, especially for automotive and stationary applications. PEMFCs are considered to be one of the most promising and viable power sources, useful not only for terrestrial applications but also for aerospace applications [1–3], including super-pressure balloons and moon explorations, which require small and light power systems at moderate operating temperature.

In general, reactants, such as hydrogen and oxygen, need to be excessively supplied to PEMFCs operating at low temperatures to prevent reactant starvation and to remove product water, which might lead to flooding that hinders the reactants from reaching the reaction sites inside the cell. Unreacted reactants and product water are discharged from the fuel cell outlet. However, discharging them into the ambient atmosphere reduces the reactant utilization of the fuel cell system. Unreacted hydrogen in the stationary applications can be burned and the produced heat is utilized for fuel reformers [4]. In applications without reformers, on the other hand, dead-end or recirculation systems are employed to minimize the reactant wastage.

Dead-end operations are those in which the outlet of the fuel cell is sealed to achieve high reactant utilization, and such systems are often employed [5–12]. Fuel cell systems for dead-end mode operations are very simple because of the absence of recirculation devices such as pumps and ejectors. However, the product water is prone to accumulate in the cell because of a lack of forced convection in the dead-end mode, which eventually causes the flooding and deterioration of the cell performance in the form of voltage decline. In general, water is produced in the cathode; however, even in the anode, water films and droplets can be found because of vapor condensation and back-diffused product water from the cathode. Therefore, periodic purging [5,6] or continuous purging [7,8] with a small flow rate is necessary to refresh or maintain the cell performance. During purging, the unreacted reactants are unavoidably discharged with the product water into the ambient atmosphere. In addition, purging causes the cell voltage in the dead-end mode to vary significantly, because the purging process starts when a predefined low voltage level is detected, and it is completed when either a certain period of time has elapsed or the cell has recovered a certain voltage level.

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The fuel cell systems for large energy applications employ a reactant recirculation system in which the unreacted reactants discharged from the outlet of the fuel cells are recirculated back to the inlet to minimize the reactant wastage [2,3]. The recirculation systems achieve a stable and durable operation without periodic purging processes, because continuous forced flow produced by the recirculation device can prevent water buildup in the cell. Conventional recirculation systems use mechanical pumps that consume electrical power and generate vibration and noise. In addition, the pumps consist of several mechanical components that are not desirable in terms of reliability and simplicity. Since the major advantages of fuel cells over conventional combustion generators include high efficiency, tranquility, and lack of vibration, the need to use mechanical pumps qualitatively neutralizes such benefits. Furthermore, the technical difficulty of hermetically sealing the fuel cell system can arise, because the pumps consist of special sealing parts such as bearings, diaphragms, and lubricants, all of which provide opportunities especially for hydrogen, the smallest molecule, to escape.

Ejectors can recirculate the unreacted reactants without using moving parts, and they have been studied for fuel cell recirculation systems [13–21]. They are advantageous over mechanical pump-based recirculation systems in terms of mechanical reliability and efficiency, and hence, they are considered promising. However, they are still under research and sophisticated computed fluid dynamics (CFD) analyses are necessary to design ejectors. Moreover, the ejectors operate almost passively and their performance is strongly influenced by their geometry and working conditions; hence, additional moving parts might be required to realize a wide operating range [18]. In the case of operations without the additional moving parts, the ejectors may work unstably during startup, shut-down, and load changes because their performance is inconstant in a low flow rate region, i.e., a low current density region for fuel cells. The flow characteristic in the low flow rate region tends to become complicated and unexpected fluctuations in the recirculation line could occur [19,20]. In addition, the influence of water existence in the unreacted reactant on the ejector performance is also a concern [21].

In this paper, we propose a pumpless reactant recirculation system, the pressure swing recirculation system, which utilizes pressure increase and decrease produced by reactant supplies and consumptions. Instead of recirculation devices, only two check valves and a fluid control device are required for recirculation. The fundamental operating principles, major benefits, control strategies for recirculation, and influence of pressure swing on the cell performance in the proposed system are explained and discussed. The pressure swing recirculation systems were built separately for both the anode and the cathode of a PEMFC. The experimental stability performance tests for a single cell supplied with pure hydrogen and oxygen were performed in both dead-end and pressure swing recirculation modes.

2. Pressure swing recirculation systems

2.1. Pressure swing recirculation in pressure-controlled mode

A schematic diagram of the proposed pressure swing recirculation system is shown in Fig. 1. For simplicity, only the anode system without a humidifier is depicted. Only two check valves and a fluid control device are needed for recirculation. A pressure controller is employed as the fluid control device for the pressure-controlled pressure swing recirculation. The reactant pressure of the fuel cell inlet is measured and controlled by the pressure sensor and the pressure controller, respectively. In this configuration, the pressure is directly controlled by the pressure controller, while the flow rate of the pressure controller is indirectly determined by the increase rate of the pressure, consumption rate of the reactant, and fluid volume of the piping. The pressure swing recirculation system operates in two modes, A and B, and these two modes alternate with each other. Reactant flow directions in each mode are depicted in Fig. 2(a) and (b), respectively. The theoretical operating waveforms are illustrated in Fig. 3. In the proposed system, the pressure varies between the predefined upper and lower limits, P_U and P_L, respectively.

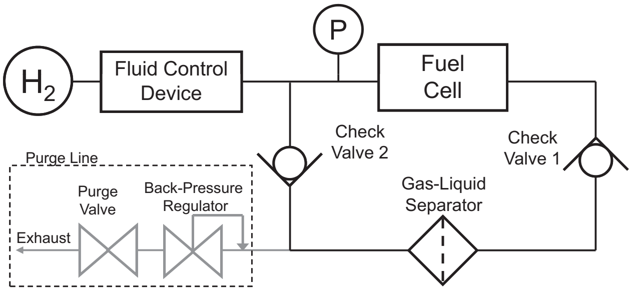

Fig. 1. Schematic diagram of pressure swing recirculation system.

In mode A, during the reactant supply period, the pressure controller increases the reactant pressure from P_L to P_U by introducing reactant into the fuel cell. The reactant supply rate must be greater than the reactant consumption rate in order to increase the pressure. The flow rate of the pressure controller, q_{in}, is expressed as

$$q_{in} = p_A C + q_{FC} = p_A(C_{\text{Cont}} + C_{\text{Check}}) + q_{FC} = p_A C_{\text{Cont}} + q_{CV1} + q_{FC}, \qquad (1)$$

where p_A is the pressure increase rate in mode A (i.e., the pressure increase per unit time), C is the total fluid volume, C_{Cont} is the fluid volume between the pressure controller and check valves (i.e., the volume of flow channels in the cell and the volume of piping directly connected to the cell), C_{Check} is the fluid volume of piping between check valves 1 and 2, q_{FC} is the reactant consumption rate, and q_{CV1} is the flow rate of the check valve 1.

As shown in Fig. 2(a), a part of the unreacted reactants passes through check valve 1 at a flow rate of q_{CV1}. Therefore, mode A

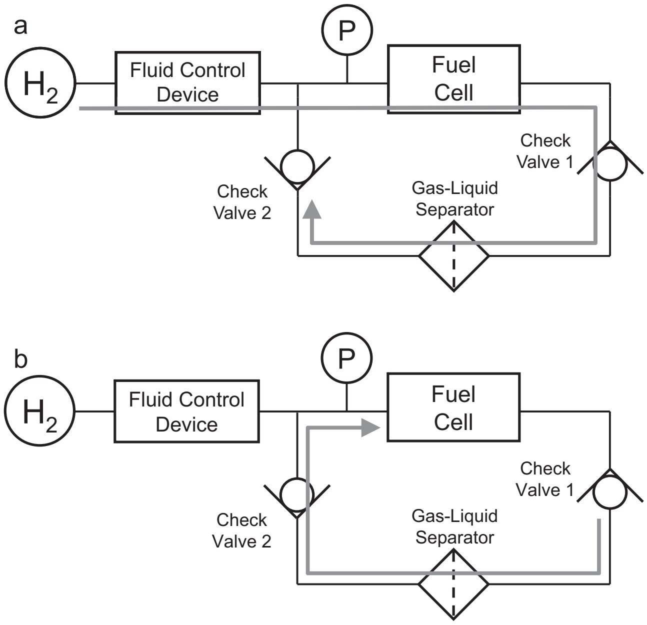

Fig. 2. Reactant flow directions in (a) mode A and (b) mode B.