Journal of Power Sources 272 (2014) 743–752

Contents lists available at ScienceDirect

Journal of Power Sources

journal homepage: www.elsevier.com/locate/jpowsour

Transient analysis of gas transport in anode channel of a polymer electrolyte membrane fuel cell with dead-ended anode under pressure swing operation

Yasushi Ichikawa [a, b, *], Nobuyuki Oshima [b], Yuichiro Tabuchi [a], Keigo Ikezoe [a]

[a] *EV System Laboratory, NISSAN Motor Co., Ltd., Japan*
[b] *Graduate School of Engineering, Hokkaido University, Japan*

HIGHLIGHTS

- Stable operation of full-scaled single fuel cell achieved with dead-ended anode.
- Gas concentration in the anode channel is measured continuously by mass spectrometry.
- Gas behavior in the channels quantitatively determined by transient fluid simulation.
- H_2 supply by pressure swing operation generates oscillatory flow.
- A design tool for pressure swing supply in dead-ended anode on a PEFC is developed.

ARTICLE INFO

Article history:
Received 2 June 2014
Received in revised form
21 August 2014
Accepted 3 September 2014
Available online 16 September 2014

Keywords:
Polymer electrolyte fuel cell (PEFC)
Mass transport
Dead-ended anode operation
Pressure swing supply of hydrogen
Oscillatory flow

ABSTRACT

Further cost reduction is a critical issue for commercialization of fuel-cell electric vehicles (FCEVs) based on polymer electrolyte fuel cells (PEFCs). The cost of the fuel-cell system is driven by the multiple parts required to maximize stack performance and maintain durability and robustness. The fuel-cell system of the FCEV must be simplified while maintaining functionality. The dead-ended anode is considered as a means of simplification in this study. Generally, if hydrogen is supplied under constant pressure during dead-ended operation, stable power generation is impossible because of accumulation of liquid water produced by power generation and of nitrogen via leakage from the cathode through the membrane. Herein, pressure oscillation is applied to address this issue. Empirical and CFD data are employed to elucidate the mechanism of stable power generation using the pressure swing supply. Simultaneous and time-continuous measurements of the current distribution and gas concentration distribution are also conducted. The results demonstrate that the nitrogen concentration in the anode channel under pressure constant operation differs from that under pressure swing supply conditions. The transient two-dimensional CFD results indicate that oscillatory flow is generated by pressure swing supply, which periodically sweeps out nitrogen from the active area, resulting in stable power generation.

1. Introduction

Although fuel-cell electric vehicles (FCEVs) are very promising as zero emission vehicles (ZEVs), widespread commercial use of these vehicles has not yet been realized. The cost of FCEVs is one of the major hindrances to commercialization, and thus, cost reduction is imperative to make these vehicles available to the general public through mass-production. As prospective means of cost reduction, simplification of the system and reduction of the number of subsystem components are necessary while maintaining the requirements of the fuel-cell system.

Conventionally, a recirculation system is used for anode supply [1] as shown in Fig. 1a. In this system, hydrogen is supplied in excess of the consumption requirement for power generation. The unreacted hydrogen gas returns from the outlet of the stack of the fuel cell to the upstream region of the stack, and is supplied again to the inlet of the stack with fresh hydrogen. Under high humidity conditions, the anode fluid can flow through the anode gas channels in the fuel cells or gas path in the stack at a sufficiently high flow rate to sweep out inert gas or liquid water from these areas, and the hydrogen concentration is thus kept uniform within the

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* Corresponding author. EV System Laboratory, NISSAN Motor Co., Ltd., 1 Natsushima-Town, Yokosuka-city 237-8523, Japan. Tel.: +81 46 867 5348.
E-mail addresses: yasushi7_mac@mac.com, yasu-ichikawa@mail.nissan.co.jp (Y. Ichikawa).

http://dx.doi.org/10.1016/j.jpowsour.2014.09.023
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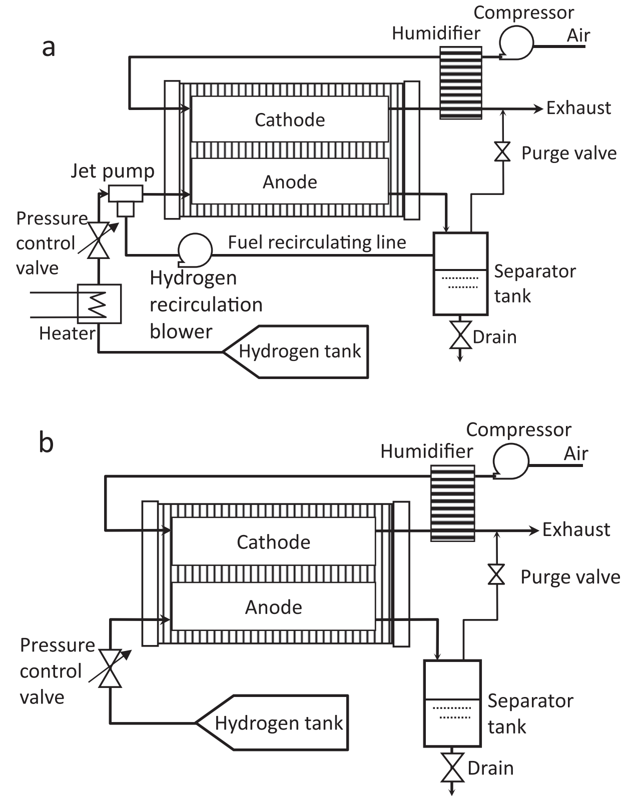

Fig. 1. a) A conventional anode supply system. b) An anode dead-ended supply system.

active area of the fuel cells. Furthermore, under low humidity conditions, this recirculation flow can help to humidify the fuel cells by returning water vapor from the outlet of the stack. To achieve a sufficiently high flow rate, a pumping sub-device such as a hydrogen recirculation blower (HRB) or a jet-pump (ejector) is required [2]. Here, water (whether in the vapor or liquid phase) is produced during the power generation process and this water contributes to the draw performance of the fuel cell. Inert nitrogen gas comes from the air introduced into the cathode channel by permeating through the polymer electrolyte membrane (PEM) in the fuel cell, where this permeation is driven by a concentration gradient [3]. However, unfortunately, the utilization of these pumping devices themselves leads to increased costs and the additional requirement for heating devices in order to prevent freezing under sub-zero temperature start-up conditions. Furthermore, the incorporation of these devices leads to a weight increase and capacity increase, and causes net power loss given that the pumping devices require electric power for operation. Therefore, power generation without the use of these sub-devices is an emerging key point for practical implementation of FCEVs.

Thus, when simplification of the anode system is taken seriously with the expectation that the anode recirculation system will be phased-out, the prime candidate replacement system component is the dead-ended anode shown in Fig. 1b [4]. If stable power generation can be achieved with the dead-ended anode system, the cost reduction issue can be resolved. However, based on evaluation of the performance of the anode dead-ended fuel cells from intensive studies on the laboratory scale [5–8] and practical size scale [9,10], it has been reported that the cell voltage declines over time. Thus, it has not been possible to maintain stable power generation under a constant pressure supply with the dead-ended anode system. This instability was attributed primarily to accumulation of the nitrogen from the air introduced into the cathode channel that permeated the PEM from the cathode side. When only inert nitrogen gas was accumulated in the downstream region of the gas channels, an area of high concentration and an area of low concentration of hydrogen were both present on the single active area. Thus, two areas co-existed, one in which power generation was possible and the other in which power generation was not possible. With continued accumulation of the inert nitrogen gas, the area where the hydrogen concentration is low increased, leading to an increase in the current density of power generation in the area where the hydrogen concentration was high, and eventually, the current density reached a limiting current density [11–14].

Furthermore, it was reported that in addition to the cell voltage drop, the decline in the hydrogen concentration also causes carbon corrosion in the catalyst due to local hydrogen starvation on the active area [15,16]. When carbon corrosion occurs, the carbon supporting the platinum particles disappears in the catalyst layer, which leads to fatal destruction of an important system component. This is non-recoverable damage that results in significant failure of the fuel-cell system. In other words, hydrogen starvation on the active area must be prevented for assurance of the cell performance as well as the durability and robustness of the fuel-cell system.

To prevent degradation due to hydrogen starvation on the active area of the dead-ended anode system, nitrogen and liquid water at the end of the fuel cell in the downstream region of the gas channels must be discarded; the removal of these inert materials from the active area is termed “purging”. Continuous purging results in loss of a large amount of unused hydrogen, which causes a decline in the vehicle mileage, and thus this approach is not suitable. Intermittent purging results in a drop in the cell voltage at the end of one purging cycle, thus, fluctuation of the cell voltage occurs over the duration of the purging cycle. The purge frequency should be sufficiently high to at least maintain the cell voltage [12,17]. A balance between purging at an optimized frequency to retain as much unused hydrogen as possible [18,19] and maintaining stability of the cell voltage must be achieved, given that fluctuation of the power generation due to fluctuation of the cell voltage generally results in difficulty in controlling the vehicle.

Therefore, in order to utilize system components similar to the existing ones without the recirculation line, pressure swing supply is one potential solution, even with the dead-ended anode system where localization of the hydrogen concentration does not occur. In this system, oscillating flow is generated in the gas channel in the anode side of the fuel cell by intermittent supply of hydrogen with some inevitable buffer volume that localizes downstream of the fuel-cell stack, similar to the case of a tube or a water separator tank, as shown in Fig. 1b. In the case of pressure swing supply, it has been reported that hydrogen concentration in the gas channel on the active area becomes more uniform than in the case of pressure constant supply [20]. The application of the dead-ended anode system with pressure swing supply to a prototype vehicle has been demonstrated [21].

For deeper understanding of mass transfer from the inside of the anode gas channel to the outside, we evaluate, herein, the longitudinal concentration distribution under both pressure swing and pressure constant hydrogen supply with the dead-end anode based on experimental and CFD analysis. The experiments employ time-continuous gas sampling along the gas channel of the working single cell, and the CFD analysis employs two-dimensional transient calculations. The mechanism by which inert nitrogen gas is swept out under laminar flow and low frequency (maximum Reynolds number $Re = 16.5$, Womersley number $Wo \cong 0.04$) conditions is expounded in this study.