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Development and testing of a hybrid system with a sub-kW open-cathode type PEM (proton exchange membrane) fuel cell stack

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ABSTRACT

In this study, the performance of a polymer electrolyte membrane fuel cell stack has been evaluated for a hybrid power system test platform. To simulate vehicle acceleration, the stack was operated under dynamic-loading, and to demonstrate the exchange of power flow between two power sources the hybrid power system was tested under three different modes. A unit cell was fabricated for high stack performance and the stack was constructed with 18 open-cathode type fuel cells. Air which acts as a coolant as well as an oxidant for electrochemical reactions is provided by a pair of fans. The capabilities of the stack for hybrid power system test platform were validated by successful dynamic-loading tests. The performance of the stack for various air fan voltage was evaluated and an optimal value was concluded. The conditions like inlet temperature of H_2 and the stack current were established for maximum power. It was also found that humidification of hydrogen at anode inlet degrades the stack performance and stability due to flooding. Evidence shows that for the higher overall performance, the fuel cell acts continuously on constant current output. The study contributes to the design of mobility hybrid system to get better performance and reliability.

1. Introduction

Despite improvements in the past decades on conventional ICE (internal combustion engine) technologies, air pollution and greenhouse gas emission from automotive vehicles are a persistent problem in populated cities all over the world. EVs (electric vehicles) powered by Li-ion batteries offer advantages such as high energy efficiency and zero emission over the vehicles powered by ICE [1]. However, the cruise range of EVs per battery charge is less competitive to the vehicles with ICE and this drawback is responsible for their slow market penetration. The limitations of the battery storage systems of EVs motivate the research to reduce the charge cycle of battery and improve the driving range per charge cycle. To date the most promising vehicle engine that can overcome the problems of present ICE technologies is fuel cells powered by hydrogen. When compared with EVs, vehicles with fuel cells have advantages of long driving distance with a very short refilling time. The advantages like high power density, efficiency, fast start-up, low noise and zero emission make PEMFCs (polymer electrolyte membrane fuel cells) to be the most competitive candidate for automobile applications [2,3,4,5,6,7]. PEMFCs, which utilize hydrogen as the fuel and only emit water as the byproduct, have undergone rapid development since the 1990's. In addition to applications for vehicles, PEMFCs also have great potentials to be a green power source for computers, communication, consumer electronic products, material handling and stationary power, and so on.

A typical fuel cell system consists of three sub-systems as: an anode loop, a cathode loop and a cooling loop. Collectively they are referred as the BOP (balance of plant). In a PEMFC stack, efficient thermal and gas management is vital in order to ensure optimal operation [8,9]. Large PEMFC stacks often requires liquid cooling, but small stacks (kW or sub-kW) can be operated in an open-cathode mode with air supplied by fans [9,10]. This reduces the overall complexity of the PEMFC system since liquid coolant loops, plates and radiators are not required. The operation of air-cooled PEMFC stacks involves delivery of ambient air and the components of flow delivery depends on the size, power and operating conditions of the fuel cell stack [11,12]. The air flow rate must be high enough to satisfy both stoichiometry and cooling requirements. In this configuration, air is forced to flow through the cathode channels to ensure the amount of oxygen needed for the

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cathodic electrochemical reaction, and to remove excessive heat by forced convection [5]. Thus the stack temperature is maintained in an optimal range. On the other hand, the operating conditions such as stack temperature, which needs to be high enough to enable electrochemical reaction kinetics, may lead to membrane dehydration, thus increasing ohmic loss of the stack [13]. The amount of water absorbed influences the proton transport, which alters the ionic conductivity of a PEM (proton exchange membrane) [14,15]. Accumulation of liquid water in the fuel cell components may hinder reactants' mass transfer and result in fuel or oxidant starvation [16,17,18]. Since the cooling loop constitutes a large portion of the stack system, alternative methods of cooling such as the open-cathode design is ideal [19,20]. The open-cathode design simplifies the stack system, by eliminating parasitic components such as coolant manifold and pump.

The amount of air needed for cooling purposes (and its inherent pressure drop) for an open-cathode PEMFC stacks has been, estimated by a 1D theoretical model [9]. The results from the above literature has been used to select the appropriate axial fans to assemble the cooling system for a 2 kW prototype developed in facilities. Even when its performance is far to be considered optimal, a power of 1300 W has been obtained in the preliminary tests performed. An open-air cathode PEMFC (proton exchange membrane fuel cell) was developed and the effect of several critical operating conditions on the performance of 8-cell stack was studied [10]. Objective of the study was to identify a situation when the PEMFC stack can be used in low-power portable applications. PEM fuel cells with ambient force-feed air-supply and their stack was designed [19]. The air for the cathode was directed from ambient atmosphere with variable humidity and the flow rates were controlled in order to simulate their effects on the cell performance under real conditions. When an integrated porous, hydrophilic, electrically conductive layer was coupled to an electro osmotic pump for active removal of water from the cathode side of the fuel cell; the pump consumed only 2% of the power output from the fuel cell [21]. The performance improvement of the open-cathode PEM fuel cell was studied to explore the effect of the structural combination of the MEA (membrane and electrode assembly) [22]. The results show that CCM (catalyst coated membrane)-based MEA with hydrophilic GDL (gas diffusion layer) gives good performance and stability even at 60 °C. A fuel cell system for application as a power source in UAVs (unmanned aerial vehicles) was designed and fabricated [23]. The hybrid power management system using an auxiliary battery was developed and evaluated for efficient energy management. The H-100 commercial product (Horizon Fuel Cell Technologies) was prepared in the form of a 100 W PEMFC stack; comprising 24 single cells. Each cell had 19.2 cm^2 active area, and used an air-breathing cathode channel. While the fuel cell supplies steady power during the cruising flight; hybrid power from the fuel cells and battery is used during takeoff and flight operations. The capabilities of the fuel cell UAVs for long endurance flights have been validated by successful flight tests.

The objective of present study is to develop a hybrid power system with a fuel cell stack and a Li-ion battery and to build a test platform to investigate the behaviour of the system. An open-cathode PEMFC stack (rated output 300 W) was fabricated to achieve an overall high stack power density. In order to remove the generated water and heat, excess air and/or additional cooling system are needed. This protects the stack from overheating, but also results in higher system complexity and cost. The open-cathode configuration simplifies the design of a stack system since parasitic components such as coolant manifold and pump can be eliminated. Experiments were carried out to investigate the characteristics of the open-cathode PEMFC stack. Performance and stability of the stack were examined. The stack was operated under dynamic-loading to simulate vehicle driving cycles. The stack was integrated with a Li-ion battery to form a hybrid system. The fuel cell stack and the motor was connected by a DC/DC converter which regulated the output power of the fuel cell stack. The Li-ion battery was used to be part of the hybrid system for effective power management. The performance of the integrated system was evaluated to assess the feasibility of combining a fuel cell stack in a hybrid system.

2. Experimental design and fabrication of fuel cell stack

2.1. Assembly of open-cathode PEMFC stack

In the present study, an 18-cell stack, hereafter termed as "YZFC-ZM", was designed and fabricated in-house based on the specifications in Table 1. The stack as sketched in Fig. 1 had open-cathode gas flow channels where air was delivered into the stack for reaction as well as to cool down the stack. The bipolar plate of the stack was made of graphite and had dimensions of 68 mm (W) × 258 mm (L) × 3 mm (T). Each unit cell had an active area of 100 cm^2. The stack was designed to output a nominal electric power of 300 W. The anode bipolar plate had 20 parallel serpentine gas channels in 4 blocks. The channel cross section was 1 mm (H) × 2 mm (W). The cathode flow field had 49 straight parallel channels, with channel cross section of 2 mm (H) × 3 mm (W), and the length these channels was the same as the width of the bipolar plates (258 mm), cf. Fig. 2. Commercial MEAs [Nanya Technology Co., Taiwan] were used in the stack. The current collector plates of the stack were made of gold plated brass. The stack was designed such that hydrogen stream was distributed through individual cells in series. Two air fans were installed on the stack to supply air and to remove heat from the system, cf. Fig. 3. The air fan was normally operated at 10.5 V, or otherwise specified. Specifications of the fans used in the YZFC-ZM stack, including air velocity, flow rate, current/power drawn by the fans as functions of applied voltage, are tabulated in Table 2. Dry hydrogen of 99.9% purity was used for all fuel cell tests, or otherwise noted. A 500 W PEM Fuel Cell Testing Station (Scribner 890C Fuel Cell Test) was employed for a series of experiments, including modes of scan voltage, constant voltage, constant current, and dynamic load response. The stack was tested under constant voltage to obtain polarization curves and under constant current to test the stability of stack performance. To simulate a rapid start-up procedure, dynamic load conditions were applied.

2.2. Test platform for hybrid power system

The YZFC-ZM stack was mainly operated at a stable output power of about 240 W (20 A). The stack was connected to a motor

Table 1
Specification of a YZFC-ZM stack.

Item	Specification
Stack dimensions	140 L × 258 W × 100 H
Stack weight	5.7 kg
Active area (cm^2)	100 cm^2
MEA manufacturer/type	Nafion 112, Ion Power, Inc.
Catalyst loading (mg cm^{-2})	Anode: Pt/C 0.2 Cathode: Pt/C 0.4
Gas inlet type	Anode: dead end Cathode: air fans cathode
Cell number	18
Flow-field type	4 serpentines
Fuel	H_2/Air
Power	About 300 W
Cooling type	Gas cooling