



Development of porous carbon foam polymer electrolyte membrane fuel cell

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ABSTRACT

In order to prove the feasibility of using porous carbon foam material in a polymer electrolyte membrane fuel cell (PEMFC), a single PEMFC is constructed with a piece of 80PPI (pores per linear inch) Reticulated Vitreous Carbon (RVC) foam at a thickness of 3.5 mm employed in the cathode flow-field. The cell performance of such design is compared with that of a conventional fuel cell with serpentine channel design in the cathode and anode flow-fields. Experimental results show that the RVC foam fuel cell not only produces comparative power density to, but also offers interesting benefits over the conventional fuel cell. A 250 h long term test conducted on a RVC foam fuel cell shows that the durability and performance stability of the material is deemed to be acceptable. Furthermore, a parametric study is conducted on single RVC foam fuel cells. Effect of geometrical and material parameters of the RVC foam such as PPI and thickness and operating conditions such as pressure, temperature, and stoichiometric ratio of the reactant gases on the cell performance is experimentally investigated in detail. The single cell with the 80PPI RVC foam exhibits the best performance, especially if the thinnest foam (3.5 mm) is used. The cell performance improves with increasing the operating gauge pressure from 0 kPa to 80 kPa and the operating temperature from 40 °C to 60 °C, but deteriorates as it further increases to 80 °C. The cell performance improves as the stoichiometric ratio of air increases from 1.5 to 4.5; however, the improvement becomes marginal when it is raised above 3.0. On the other hand, changing the stoichiometric ratio of hydrogen does not have a significant impact on the cell performance.

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1. Introduction

The environmental consequences of fossil fuel use for the propulsion of vehicles and in production of electricity have become one of the major concerns which have greatly influenced the development of fuel cells. Fuel cells are electrochemical energy conversion devices that convert chemical energy stored in the reactants into electrical energy with high efficiency. They produce potentially useful heat and pure water as the only major byproducts. Amongst the existing fuel cell technologies, the polymer electrolyte membrane fuel cell (PEMFC) has been most actively and widely researched owing to many beneficial features including low temperature operation, fast start-up, high power density, system robustness, potential of compactness, lightweight, and low emissions [1]. Therefore, the majority of motor manufacturers and energy companies are enthusiastically pursuing the PEMFC research and development for the commercialization of PEMFC.

However, the wide-spread commercialization of PEMFC has been hindered because of existing technical barriers such as catalyst CO poisoning; air, thermal, and water management; cell durability and reliability; and fuel cell material manufacturing and system operating costs [2]. One of the biggest challenges to the commercialization of PEMFC is still the cost reduction of the fuel cell components which is mainly attributed to the use of expensive materials such as precious metal catalysts, Nafion[®] electrolyte membrane, and graphite plates [3].

Conventional PEMFC technology uses machined channel design in the gas flow-field of the bipolar/end plate which is considered as one of the most significant and expensive components accounting for as much as 60% of the total cell cost and responsible for more than 80% of the total cell weight [3,4]. Flow-field channels are generally machined on Poco[™] graphite plates which exhibit good performance with strong resistance to corrosion in the fuel cell environment; however, they are brittle, expensive, bulky, and difficult to machine channels on [1]. PEMFC performance is largely determined by electrical conductivity of the flow-field plate and mass transport in the flow-field channels because water flooding and concentration distribution are the most significant phenomena controlled by the flow-field channel configuration [3]. It was theoretically and experimentally proven by many research

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Nomenclature

A_e	effective surface area of distribution of the reactant gas in the in-plane direction, m^2
A	cross-sectional area, m^2
D	effective pore diameter, m
F	Faraday's constant, $C\ mol^{-1}$
I	current, A
k	gas permeability of the medium, m^2
L	distance from the inlet (point a) to the outlet (point b) of the medium, m
l	length (equivalent to the RVC foam thickness), m
$p_b - p_a$	pressure drop between the inlet (point a) and the outlet (point b) across the medium, Pa
Δp_{ca}	differential capillary pressure, Pa
p_{total}	total pressure, Pa
Q	total discharge, $m^3\ s^{-1}$
R	gas constant, $J\ mol^{-1}\ K^{-1}$
R_e	electrical resistance, Ω
T	temperature, K

Greek letters

ρ	resistivity of the material, $\Omega\ m$
ν	dynamic viscosity of the reactant gas, Pa s
γ	surface tension of liquid water, $N\ m^{-1}$
θ	contact angle of liquid water with the pore surface, ° of spreading

Subscripts and superscripts

FC-A	RVC foam fuel cell design
FC-B	conventional fuel cell design
GDL	gas diffusion layer
MPL	micro-porous layer
PEMFC	polymer electrolyte membrane fuel cell
PPI	pores per linear inch
RVC	Reticulate Vitreous Carbon

groups [3,5–8] that good water management and high fuel consumption rate can be attained by carefully controlling the channel gas permeability, which is defined as a measure of the ability of the medium to transfer liquid/gas through it. Decreasing gas permeability increases gas flow resistance in the flow-field channels and makes the transport of the reactant gas toward the reaction interface undergo forced convection mechanism in addition to concentration diffusion mechanism [9]. However, gas permeability in the channel design cannot go below $10^{-8}\ m^2$ because machining very thin cross-section channels on graphite plates to achieve such low gas permeability is a very expensive and difficult process [9]. Moreover, producing channels narrower than 0.5 mm is practically impossible, especially if low production cost is to be maintained [5,6].

Many research groups [3,5–7,9–11] have shown that using porous material in the flow-field provides many alluring benefits over the conventional flow-field channel design including capability of reducing gas permeability, higher uniformity of mass transport and local current density, and enhanced heat and water management with better two-phase flow distribution as a result of intensified capillary action in the porous structure. So far, porous metal foam is commonly used as an alternative that has strong potential to replace the conventional flow-field channel design [3,9–12]. However, because of the corrosive operating fuel cell environment, catalyst poisoning due to metal corrosion and reduced electrical conductivity due to oxide layers forming on the surface are the main issues associated with the metal/alloys

systems [13–15]. As an alternative to the metal foam, carbon foam exhibits advantageous characteristics such as high corrosion-resistance, good thermal conductivity, and low electrical resistivity [7,16]. Using porous carbon foam serving as a gas distributor in the cathode was previously suggested by Senn and Poulikakos [7], and a concept of foam fuel cell based on open cell vitreous carbon foam serving as a gas distribution layer was described over 30 years ago [17]; however, very little work has been published on the subject since. Therefore, the current study focuses on exploring a new fuel cell design concept: Reticulated Vitreous Carbon (RVC) foam was employed as an alternative to the traditional machined channel design in the cathode flow-field of a single PEMFC. As an experimental control, a conventional fuel cell with serpentine channel design employed in the anode and cathode flow-fields was developed and its experimental result was compared with that of the RVC foam fuel cell to verify the feasibility of using the RVC foam in the cathode flow-field. Furthermore, performance of the foam fuel cell is investigated in detail.

Performance of a PEMFC is greatly affected by several factors including operating conditions, mass transport phenomena, electrochemical reaction kinetics, and geometry and morphology of the fuel cell components [18]. Therefore, having a good understanding of the impact of operating variables on the cell potential is strongly required in order to maximize the cell efficiency. For a standard PEMFC, the typical operating conditions studied include cell temperature, operating pressure, humidity and stoichiometric ratio of the reactant gases; these operating variables can be controlled during the operation. However, other parameters such as geometrical and material parameters of the fuel cell components including gas permeability of the flow-field and its design, morphology of the gas diffusion electrode, catalyst loading, and different electrolyte membrane thickness and its type cannot be modified during the fuel cell operation [19]. It is therefore critical to understand the impact of those parameters (either intrinsic to the cell construction or selected during the operation) on the cell performance. Amongst the intrinsic parameters, the flow-field design and shape is one of the most studied; therefore, understanding how the flow-field design influences the performance is of great interest to both researchers and fuel cell manufacturers. Many theoretical and experimental works focusing on understanding the interaction between the flow-field design and the cell performance have been published [9,19–25].

Several research groups have proposed and developed many novel fuel cell design concepts in which porous foam material is employed in the flow-field of a PEMFC [3,5,7,9–11]. However, parametric studies on such novel fuel cell designs have not been carried out in great detail, and their experimental data are not easily available in the open literature. The parametric study, which describes behavior of the fuel cell operation under various operating conditions and geometrical and material parameters of the fuel cell components, provides very important information to fuel cell developers for optimizing fuel cell design and operation. Optimization of operating conditions and geometrical and material parameters of the porous material can also lead to a better understanding of the impact of those on the cell performance. Therefore, the present paper also focuses on a parametric study in which the overall performance of the RVC foam fuel cell is experimentally investigated as a function of various operating conditions and material parameters of the RVC foam. Polarization curves, which express the characteristics of the fuel cell operation, are employed as the principal indicator to show the effect of the RVC foam parameters and the operating conditions on the performance of the RVC foam fuel cell to determine the optimum operating conditions and parameters for a successful PEMFC operation.

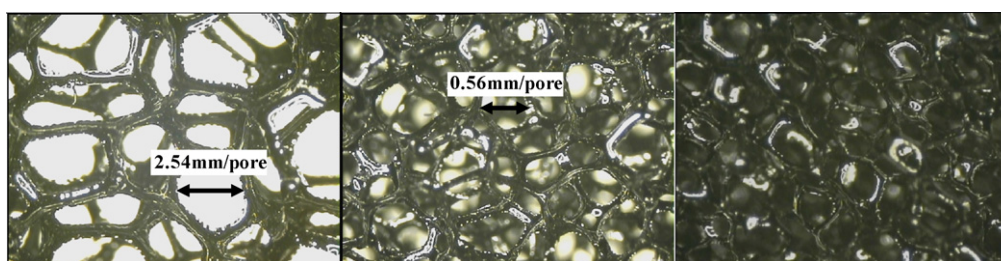


Fig. 1. Open pore structure of the RVC foam at various pore sizes (45, 60, and 80PPI).

2. Experimental/materials and methods

A set of commercially available RVC foam was purchased from Energy Research and Generation (ERG), Inc. in USA. Fig. 1 shows images of open pore structure of the RVC foam at various PPI levels. RVC foam is glass-like carbon with many open pores, and it combines the properties of glass with those of industrial carbons. Unlike other carbon-based materials such as graphite coating and carbon fiber, RVC foam is typically isotropic in nature; therefore, permeability is independent of flow direction: in-plane permeability equals through-plane permeability [16]. Advantageous material properties of the RVC foam include exceptional inertness over a wide temperature range, high electrical conductivity, good mechanical strength, uniform transport area, and low effective bulk thermal conductivity. More detailed properties of the RVC foam can be found on the supplier website [26].

For the feasibility test of the present RVC foam fuel cell design, a piece of 80PPI RVC foam at a thickness of 3.5 mm was employed in the cathode flow-field because it was the thinnest thickness available to minimize internal ohmic resistance within the cell. In a hydrogen-air fuel cell, cathode is regarded as the dominant component that significantly influences the fuel cell performance; therefore, the RVC foam was employed only in the cathode to improve water management for preventing flooding effect while ensuring hydration of the Nafion[®] membrane and to increase fuel utilization efficiency for uniformity of mass transport and local current density. Experiments for both the RVC foam fuel cell (FC-A) and the conventional fuel cell (FC-B) were performed under the operating conditions illustrated in Table 1.

The present parametric study consists of two main parts. In the first part, effect of the intrinsic material parameters of the RVC foam on the cell performance was investigated. The first intrinsic parameter studied was the effect of PPI of the RVC foam on the cell performance. Eight single RVC foam fuel cells were constructed at four different levels of PPI (45, 60, 80, and 100PPI) for the RVC foam employed in the cathode flow-field and operated under the operating conditions illustrated in Table 1. Thickness of the RVC foam for the first four fuel cells was 3.5 mm and that of the last four fuel cells was 5.0 mm. The effect of thickness of the RVC foam on the cell performance was explored as the second intrinsic parameter. Three single RVC foam fuel cells were constructed at three different levels of thickness (3.5, 5.0, and 7.4 mm) for the 80PPI RVC foam employed

in the cathode flow-field and operated under the operating conditions illustrated in Table 1. In the second part, a single RVC foam fuel cell constructed with a piece of 80PPI RVC foam at a thickness of 5.0 mm was used to investigate the effect of operating conditions including operating gauge pressure (0, 35, and 80 kPa), operating temperature (40, 60, and 80 °C), and stoichiometric ratio of the reactant gases (1.5, 3.0, and 4.5 for Air; 1.4 and 2.5 for H₂). During the analysis, only the operating condition investigated was varied, and all other parameters remained constant as defined in Table 1. Simplified descriptions of the experiments performed are summarized in Table 2. Each experiment was repeated five times, producing five polarization curves, to verify the reproducibility of the measurements. Each polarization curve represents an average of the five polarization curves taken, and each data point of the polarization curve is an average of ten experimental measurements that were collected at intervals of 30 s. Therefore, a steady-state of the cell operation was achieved when an experimental measurement was taken at a certain current density.

A piece of RVC foam completely fits into the inner hole of the graphite foam-platform designed to support the RVC foam (Fig. 2). A thin layer of carbon fiber paper (SGL 10BB by SGL Carbon Group, USA) coated with a micro-porous layer (MPL) at a thickness of 0.22 mm was inserted between the RVC foam and the foam-platform to control the depth of the RVC foam in order to minimize interfacial contact resistance due to irregular and uneven surface of the RVC foam. The same type of carbon fiber paper coated with a MPL was employed as a gas diffusion layer (GDL) and placed on both sides of the Nafion[®] membrane. Employment of the carbon fiber paper coated with a MPL offers many attractive benefits in the operation of a PEMFC and it has been studied elsewhere [27–29]. Silicon rubber gasket at a thickness of 0.25 mm was employed to seal the fuel cell.

Table 1

Standard operating conditions (load set for the minimum flow is at 5.3 A).

Parameter	Value
Reactant gases (anode/cathode)	H ₂ /air
Operating gauge pressure (anode/cathode)	35 kPa/35 kPa
Operating temperature (anode/cathode)	60 °C/60 °C
Relative humidity (anode/cathode)	100%/100%
Stoichiometric ratio (H ₂ /air)	1.4/3.0
Flow rate (H ₂)	0.8 cm ³ s ⁻¹ + Load based flow
Flow rate (air)	1.0 cm ³ s ⁻¹ + Load based flow

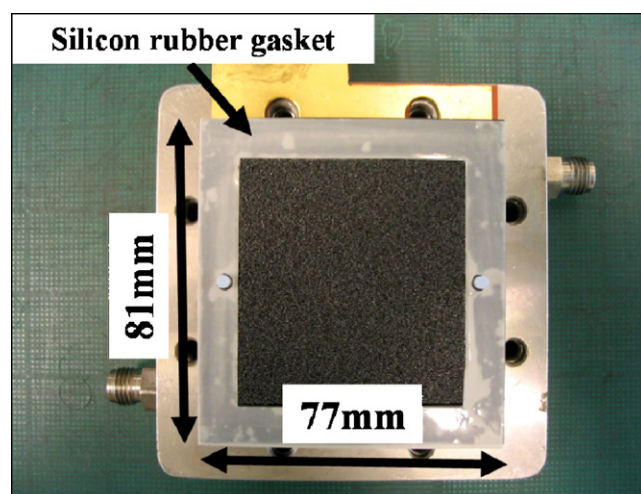


Fig. 2. RVC foam placed in the cathode graphite foam-platform.

Table 2
Detail of the experiments performed.

Type of test	RVC foam parameters	Operating conditions
PPI effect (1)	PPI: 45, 60, 80, and 100 Thickness: 3.5 mm	Operating gauge pressure: 35 kPa Other operating conditions: as illustrated in Table 1
PPI effect (2)	PPI: 45, 60, 80, and 100 Thickness: 5.0 mm	Operating gauge pressure: 35 kPa Other operating conditions: as illustrated in Table 1
PPI effect (3)	PPI: 45, 60, 80, and 100 Thickness: 5.0 mm	Operating gauge pressure: 0 kPa Other operating conditions: as illustrated in Table 1
Thickness effect	PPI: 80 Thickness: 3.5, 5.0, and 7.4 mm	Operating conditions: as illustrated in Table 1
Pressure effect	PPI: 80 Thickness: 5.0 mm	Operating gauge pressures: 0, 35, and 80 kPa Other operating conditions as illustrated in Table 1
Temperature effect	PPI: 80 Thickness: 5.0 mm	Operating temperatures: 40, 60, and 80 °C Other operating conditions: as illustrated in Table 1
Cathode flow rate effect (1)	PPI: 80 Thickness: 5.0 mm	Cathode stoichiometric ratios: 1.5, 3.0, and 4.5 Operating gauge pressure: 35 kPa Other operating conditions: as illustrated in Table 1
Cathode flow rate effect (2)	PPI: 80 Thickness: 5.0 mm	Cathode stoichiometric ratios: 1.5, 3.0, and 4.5 Operating gauge pressure: 0 kPa Other operating conditions: as illustrated in Table 1
Anode flow rate effect (1)	PPI: 80 Thickness: 5.0 mm	Various anode stoichiometric ratios: 1.4 and 2.5 Operating gauge pressure: 35 kPa Other operating conditions: as illustrated in Table 1
Anode flow rate effect (2)	PPI: 80 Thickness: 5.0 mm	Anode stoichiometric ratios: 1.4 and 2.5 Operating gauge pressure: 0 kPa Other operating conditions: as illustrated in Table 1

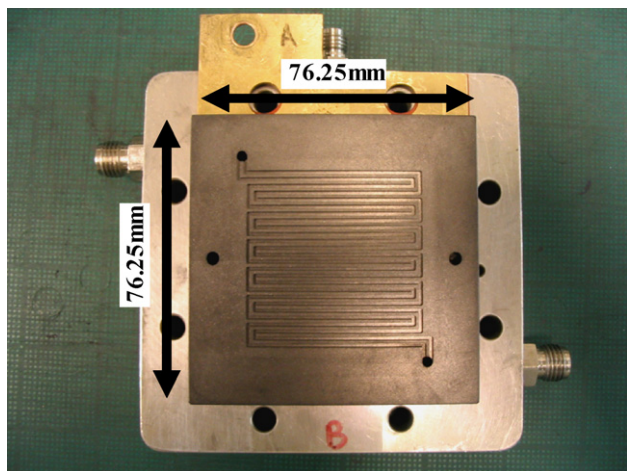


Fig. 3. Serpentine channel design of the anode flow-field.

Conventional serpentine channel design with two parallel serpentine channels was employed in the anode flow-field (Fig. 3). When the conventional fuel cell (FC-B) was developed, the graphite foam-platform in the cathode was simply replaced with a serpentine flow-field graphite plate which has the channel dimensions identical to that of the anode flow-field graphite plate. The polymer electrolyte membrane was the Nafion® 112 catalyst coated membrane manufactured by Ion Power, Inc. in USA. The electrochemical active area of the membrane was 25 cm². The membrane had a nominal thickness of 25 μm, and the catalyst loading was 0.3 mg cm⁻² of carbon-supported platinum on both the anode and cathode sides. Based on the RVC foam fuel cell schematic presented in Fig. 4, a well defined standard procedure was developed and implemented for the RVC foam fuel cell assembly. Using the foam fuel cell assembly method described above, a single RVC foam fuel cell (FC-A) for the feasibility test, a single traditional fuel cell (FC-B) for the comparison analysis, and several single RVC foam fuel cells for the parametric study were constructed and tested individually.

Fuel cell experiments were carried out at the Queen's-RMC Fuel Cell Research Centre using the Fuel Cell Automated Test Station G-60 manufactured by Hydrogenics Test Systems. The fuel cell test station is equipped with an electronic load box, a data acquisition system, back-pressure regulators, and temperature controllers for

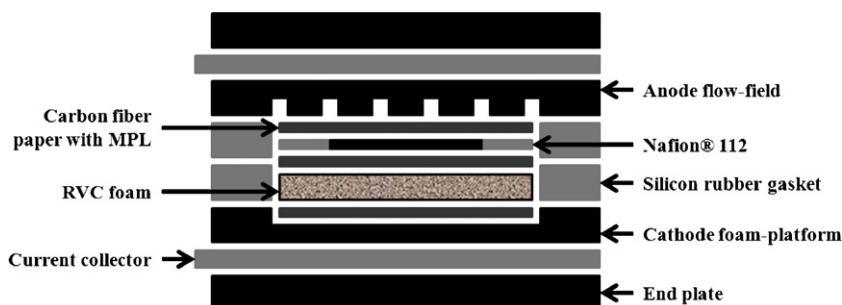


Fig. 4. RVC foam fuel cell schematic.

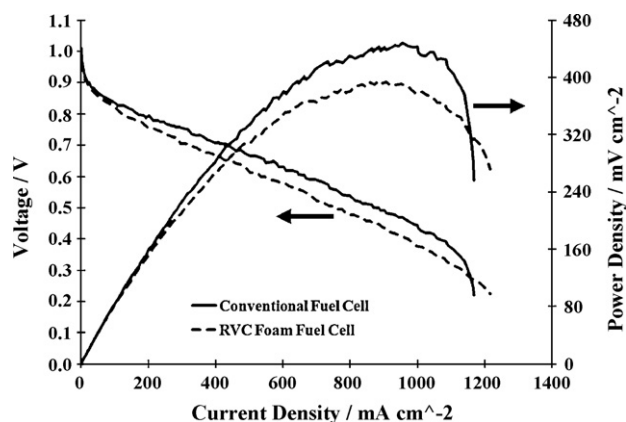


Fig. 5. Polarization and power density curves of the RVC foam fuel cell and the conventional fuel cell (operating gauge pressure: 35 kPa/35 kPa, operating temperature: 60 °C/60 °C, relative humidity: 100%/100%, stoichiometric ratio: 1.4/3.0 for anode/cathode).

the end plates, the humidifiers, and the inlet gas streams. Flow rate of the reactant gases (H_2 and air) is controlled by the mass flow controllers, and relative humidity of the inlet gas streams is controlled by the humidifiers using the direct steam injection technique with filtered deionized water. Cell voltage, current, power, flow rate of H_2 and air, inlet dew point gas temperature, inlet and outlet gas temperature, and pressure of the anode and cathode streams were recorded at predetermined intervals using the data acquisition software.

3. Results and discussion

3.1. Feasibility test

The polarization curves presented in Fig. 5 compare the performance of the RVC foam fuel cell (FC-A) and that of the conventional fuel cell (FC-B). Due to the polarization losses including activation at low current densities, ohmic at intermediate current densities, and concentration at high current densities, the voltage in the polarization curve decreases as the load increases. It was first verified with fuel cell designs developed by other research groups [27,30,19,22] that the conventional fuel cell (FC-B) used in the current study produces comparable performance to their fuel cells, especially at low current densities, under the similar operating conditions illustrated in Table 1; however, it should be noted that the fuel cell assembly methods and the material of the fuel cell components including Nafion[®] membrane with different platinum loadings and GDL used by those research groups are slightly different from the ones used in the current study. Therefore the present conventional fuel cell (FC-B) is applicable to be used for the comparison analysis with the RVC foam fuel cell (FC-A). Under the same test protocols and operating conditions illustrated in Table 1, the RVC foam fuel cell produces comparative power density to the conventional fuel cell. At low current densities lower than 200 mA cm^{-2} , there is no significant difference in performance because the equivalent Nafion[®] 112 with the same catalyst loadings was employed for both fuel cells, FC-A and FC-B. At intermediate current densities (about 500 mA cm^{-2}), the conventional fuel cell performs slightly better than the RVC foam fuel cell does. This outcome is mainly attributed to higher interfacial contact resistance existing in the RVC foam fuel cell and better electrical conductivity of the machined graphite plate than that of the RVC foam. At high current densities (about 1100 mA cm^{-2}), the conventional fuel cell (FC-B) experiences an abrupt drop in the curve, signifying that the concentration over-potential has taken place. The mass transport-limited region of the

RVC foam fuel cell is extended longer than that of the conventional fuel cell. One can suppose that the sharp drop in the tail of the polarization curve of the conventional fuel cell (FC-B) might have been observed earlier than that of the RVC foam fuel cell (FC-A) because FC-B has performed slightly better at intermediate current densities, producing a larger amount of product liquid water that can cause the concentration over-potential at high current densities. However, the difference in performance between the two fuel cells at intermediate current densities is not big enough to create a significant difference in the quantity of product liquid water. The water production rate of the two fuel cell designs can be obtained using Eq. (1) [31].

$$n_{\text{water}} = \frac{I}{2F} \quad (1)$$

where, n_{water} is the liquid water production rate (mols^{-1}), I is the current (A), and F is the Faraday's constant (C mol^{-1}). At a cell voltage of 0.4 V, the RVC foam fuel cell and the conventional fuel cell produce a current density of $972.40 \text{ mA cm}^{-2}$ and $1058.40 \text{ mA cm}^{-2}$, respectively. The water production rate of the RVC foam fuel cell at this voltage is 2.27 mg s^{-1} , and that of the conventional fuel cell is 2.47 mg s^{-1} . Difference in magnitude of the water production rate is 0.20 mg s^{-1} ; hence, it is rather negligible. This performance improvement of the RVC foam fuel cell at high current densities is most likely attributed to the presence of the RVC foam because the RVC foam is the only difference between the two fuel cell designs. Furthermore, isotropic characteristic of the RVC foam in terms of mass transfer facilitates both in-plane and through-plane mass transfer and extends the effective area in the GDL covered by the bulk flow through the porous medium, thereby enhancing overall reactant access to the active sites of the catalyst layer. Therefore, employment of the RVC foam in the cathode flow-field can promote efficient oxidant delivery and facilitate enhanced mass transport of the reactant gas and liquid water removal at high current densities for robust and stable operation by means of possessing improved self water management system within the porous structure of the RVC foam. In addition, the vertical fuel cell orientation in which hydrogen and air flow vertically provides enhanced water management because gravity plays a significant role to facilitate more efficient drainage of byproduct liquid water. Further enhancement in water management can be achieved by varying geometry of the RVC foam (i.e. elongated rectangular shape) or introducing baffle design into the RVC foam. This aspect is currently under investigation and will be presented in the future.

3.2. Stability test

A 250 h long term test was conducted on a single RVC foam fuel cell constructed with a piece of 80PPI RVC foam at a thickness of 5.0 mm to assess the stability of the present proposed design. The operating conditions of the test are outlined in Table 1, and the current density was maintained at 600 mA cm^{-2} at which the fuel cell produced a cell voltage of 0.5 V. It was experimentally proven that the RVC foam fuel cell is capable of maintaining its cell performance due to the strong corrosion-resistance characteristic of the RVC foam. It is generally known that degradation of the Nafion[®] membrane is caused by several factors such as contamination of electrocatalyst or membrane, severe operating conditions, improperly chosen material parameters, and poor dimensional stability [32]. The observed voltage degradation rates in PEMFCs that were reported by several research groups [32–35] are in the range of $10\text{--}60 \mu\text{V h}^{-1}$ under laboratory conditions. As time proceeds, the voltage decreases slightly from 0.52 V to 0.50 V after 250 h at a voltage degradation rate of $0.8 \mu\text{V h}^{-1}$. However, this voltage drop is almost negligible and it is probably caused by the degradation of the Nafion[®] membrane.

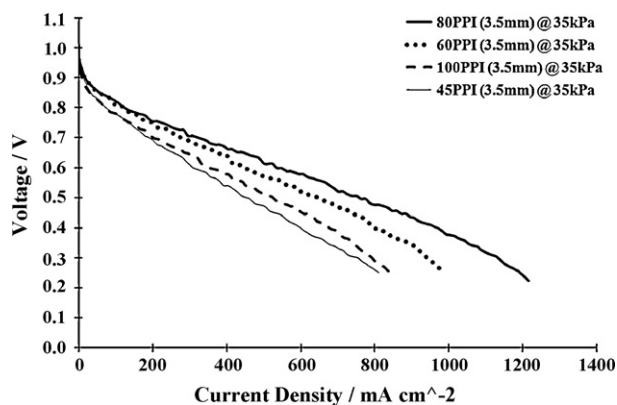


Fig. 6. Four single RVC foam (3.5 mm) fuel cells at various PPI levels (45, 60, 80, and 100PPI) tested to establish the effect of PPI on the cell performance (operating gauge pressure: 35 kPa/35 kPa, operating temperature: 60 °C/60 °C, relative humidity: 100%/100%, stoichiometric ratio: 1.4/3.0 for anode/cathode).

3.3. Effect of PPI of the RVC foam on the cell performance

Four single RVC foam fuel cells were constructed at various PPI levels (45, 60, 80, and 100PPI) while keeping the RVC foam thickness constant at 3.5 mm. Experiments were conducted on the cells under the operating conditions outlined in Table 1. The polarization curves in Fig. 6 show that the cell performance improved with an increase of PPI from 45 to 80. As the pore size of the RVC foam becomes smaller at higher PPI, mass transport resistance grows stronger within the porous structure, facilitating uniform distribution of the reactant gas in the RVC foam over the entire electrode surface. This phenomenon can be explained by Darcy's law stated in Eq. (2):

$$Q = -\frac{kA_e(p_b - p_a)}{\nu L} \quad (2)$$

where, Q is the total discharge ($\text{m}^3 \text{s}^{-1}$); k is the permeability of the RVC foam (m^2); A_e is the effective surface area of distribution of the reactant gas in the in-plane direction (m^2); L is the distance from the inlet (point a) to the outlet (point b) of the RVC foam (m); $p_b - p_a$ is the pressure drop between the inlet (point a) and the outlet (point b) across the RVC foam; and ν is the dynamic viscosity of the reactant gas (Pa s). It is assumed that Q , $p_b - p_a$, L , and ν are kept constant throughout the experiments; therefore, as k decreases at higher PPI, A_e increases. As the gas permeability decreases at higher PPI, the reactant gas penetrates deeper into the gas diffusion electrode to the catalyst layer, increasing the reactant residence time for better electrochemical reaction. Furthermore, with an increase of PPI, forced convection mass transport mechanism is enhanced in addition to concentration diffusion mass transport mechanism in the RVC foam. Yan et al. [18] claimed that the forced convection mass transport mechanism facilitates cross-flow through the GDL, making the oxygen transport rate faster and providing a larger amount of oxygen to keep up the demands required by the electrochemical reaction, even at high current densities. Moreover, strong shear force induced by the forced convection mass transport mechanism efficiently removes excessive product liquid water entrapped in the pores of the RVC foam, hence mitigating water flooding effect and increasing mass transport rate of the reactant gas and product water to and from the catalyst layer. The trend stated above that decreasing the gas permeability of the porous medium (higher PPI) would result in higher cell performance was already shown by several research groups through their experimental measurements and numerical simulations [3,5–7,9,11].

Electrical conductivity of the RVC foam has a significant impact on the cell performance. It increases as the pore size of the RVC

foam decreases, thereby improving current collection capability because the effective area of the RVC foam in contact with the membrane-electrode-assembly (MEA) and the graphite foam-platform is extended. Electrical contact resistance of the RVC foam is determined by the RVC foam parameters such as PPI and thickness and the compression pressure on the cell; it increases as the pore size of the RVC foam increases because electrons have to travel through the solid matrix of the RVC foam. As shown in Fig. 6, slope of the curve at intermediate current densities decreases as PPI increases from 45 to 80, signifying that the RVC foam at higher PPI provides higher electrical conductivity. Electrical resistances at a current density of 500 mA cm^{-2} for the 80PPI, 60PPI, and 45PPI RVC foam fuel cells are $-0.41 \Omega \text{ cm}^2$, $-0.58 \Omega \text{ cm}^2$, and $-0.72 \Omega \text{ cm}^2$, respectively—there is a linear relationship between PPI (from 45 to 80) and electrical resistance as shown in Fig. 7. This tells us that the poor performance of the 45PPI RVC foam fuel cell is mainly attributed to higher ohmic resistance existing in the 45PPI RVC foam than that in the 80PPI RVC foam.

It is interesting to notice in Fig. 6 that the cell performance at 100PPI is worse than those at 80PPI and 60PPI, but better than that at 45PPI. As shown in Fig. 7, as PPI further increases to 100, the linear relationship no longer exists and slope of the polarization curve becomes much steeper. This is probably because the pores in the 100PPI RVC foam are too small that although the reactant gas can diffuse into the active sites with enhanced convective force through the RVC foam, product liquid water, which is retained in the smaller pore network within the RVC foam and GDL, cannot effectively get removed because capillary force, which is defined as the ability of the RVC foam to draw liquid water into the pore network, might be stronger than water evaporation and shear force exerted by the gas flow. Pressure required to overcome capillary force to blow out liquid water entrapped in the pores and to facilitate a gas flow through the pores can be explained by the Young-Laplace equation [36] presented in Eq. (3):

$$\Delta p_{ca} = 4\gamma \cos \theta D^{-1} \quad (3)$$

where, Δp_{ca} is the differential capillary pressure (Pa); γ is the surface tension of liquid water (N m^{-1}); θ is the contact angle of liquid water with the pore surface ($^\circ$ of spreading); and D is the effective pore diameter (m). Although the RVC foam tends to repel water, one cannot say that it is completely hydrophobic. Since the RVC foam is not a flat surface, it is difficult to evaluate the true behavior, whether it is hydrophobic or hydrophilic. However, visual observation of water droplets in the pore network of the RVC foam showed a behavior to be in between hydrophobic and hydrophilic (contact angle close to 90°) [37,38]. From the results presented in

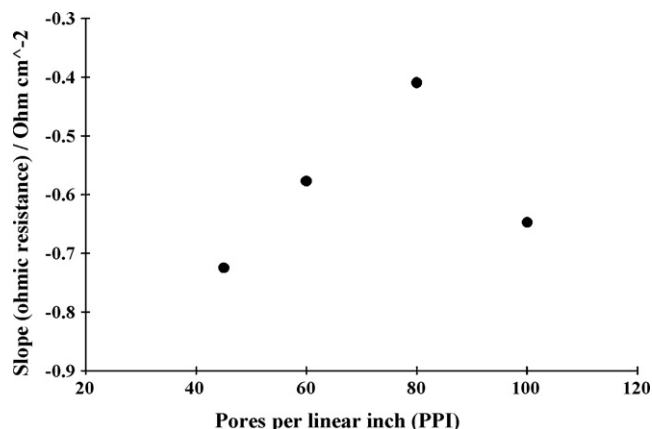


Fig. 7. Slope of the linear section (intermediate current density) of the polarization curve at each PPI (45, 60, 80, and 100).

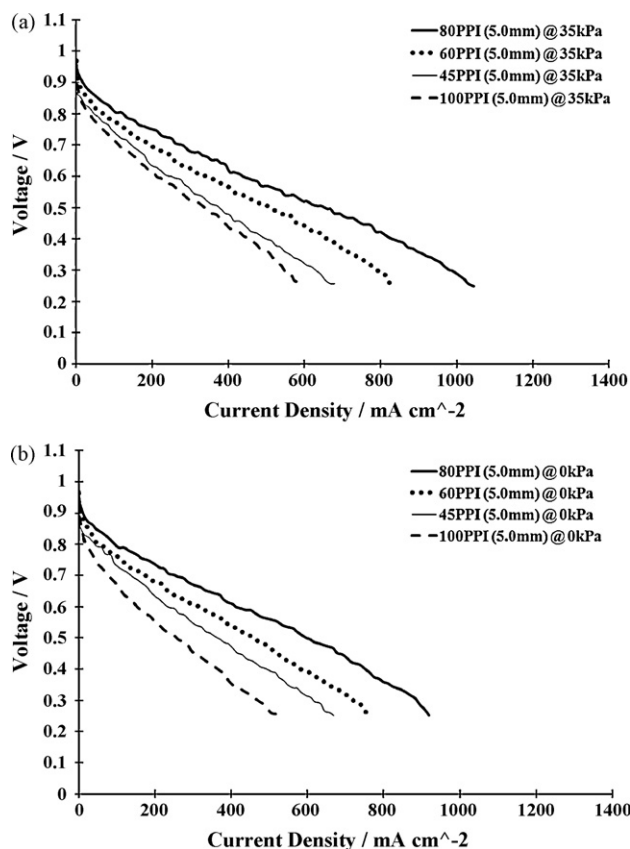


Fig. 8. Four single RVC foam (5.0 mm) fuel cells at various PPI levels (45, 60, 80, and 100 PPI) tested to explore the effect of PPI on the cell performance (operating gauge pressure: (a) 35 kPa/35 kPa and (b) 0 kPa/0 kPa, operating temperature: 60 °C/60 °C, relative humidity: 100%/100%, stoichiometric ratio: 1.4/3.0 for anode/cathode).

Figs. 6 and 7, the 100PPI RVC foam fuel cell, in spite of the fact that it provides higher electrical conductivity, experiences stronger mass transport resistance than the other RVC foam fuel cells do at intermediate and high current densities. The negative effect caused by higher mass transport resistance prevails over the positive effect of enhanced convective force for diffusion of the reactant gas and higher electrical conductivity of the 100PPI RVC foam. It is noted by Senn and Poulikakos [7] that care must be taken as to its permeability to avoid unreasonably high mass transport resistance, which is caused at excessively high PPI and has also been observed in the current study.

To further understand the effect of increasing PPI of the RVC foam, four new RVC foam fuel cells were constructed and the RVC foam thickness was changed from 3.5 mm to 5.0 mm. Fig. 8 presents the polarization curves obtained from the RVC foam fuel cells operating at the operating gauge pressure of 35 kPa and 0 kPa for (a) and (b), respectively. Similar to the results obtained previously from the old RVC foam fuel cells, the new RVC foam fuel cells showed the analogous trend—the cell performance improves from 45PPI to 80PPI, but starts to deteriorate as PPI further increases to 100. It is interesting to notice that the 45PPI performs better than the 100PPI does when the RVC foam thickness is 5.0 mm, as opposed to the previous results (Fig. 6) in which the 100PPI performs better than the 45PPI does when the RVC foam thickness is 3.5 mm. As the RVC foam thickness increases, more pores in the 100PPI RVC foam are clogged with liquid water held by stronger capillary force, making it even more difficult for the reactant gas to diffuse through the pores to the active sites. Moreover, the difference in performance between the 100PPI and the 45PPI grows bigger as the operating gauge pressure changes from 35 kPa to 0 kPa. At higher operating

pressure, a greater number of molecules of the reactant gas, given by n in the ideal gas law presented in Eq. (4), participate in the electrochemical reaction at the active sites, resulting in higher current density and improved cell performance:

$$p_{\text{total}}V = nRT \quad (4)$$

where, p_{total} is the total pressure (Pa); V is the volume (m^3); n is the number of moles (mol); R is the gas constant ($\text{J mol}^{-1} \text{K}^{-1}$); and T is the temperature ($^{\circ}\text{C}$).

There are three key parameters of the RVC foam that each can contribute to the results depicted in Figs. 6–8: porosity, permeability, and effective electrical conductivity. High gas permeability and porosity of the RVC foam (low PPI) would result in the ease of reactant flow and avoid excessive pressure drop in the flow-field; however, this would create low effective electrical conductivity which further results in increased ohmic loss across the electrical path from the current collector to the reaction sites. Low gas permeability and porosity (high PPI) would result in reduced effective area for distribution of the reactant gas in the in-plane direction and high mass transport limitation due to water flooding effect and reduced effective diffusivity. Therefore, it appears that there is an optimal porosity level to achieve the best cell performance as noted by other researchers [5,6,15].

3.4. Effect of thickness on the cell performance

In order to investigate the effect of the RVC foam thickness on the cell performance, three single 80PPI RVC foam fuel cells at various thicknesses of the RVC foam (3.5, 5.0, and 7.4 mm) were constructed and tested under the operating conditions illustrated in Table 1. Resistance to flow of electrons in the RVC foam depends on the RVC foam thickness according to Eq. (5):

$$R_e = l\rho A^{-1} \quad (5)$$

where, R_e is the electrical resistance (Ω); l is the length (equivalent to the RVC foam thickness) (m); A is the cross sectional area (m^2); and ρ is the resistivity of the material (Ωm). The RVC foam fuel cell at a thickness of 3.5 mm exhibits the best cell performance, followed by 5.0 mm and 7.4 mm. At low current densities less than 100 mA cm^{-2} , there is no significant difference in performance because the equivalent Nafion[®] 112 membrane with the same catalyst loadings was employed for the fuel cells. At intermediate and high current densities, as the RVC foam thickness increases, slope of the curve becomes steeper, signifying that stronger ohmic over-potential is induced. Ohmic resistances at a current density of 400 mA cm^{-2} for the 3.5 mm and 7.4 mm RVC foam fuel cells are $-0.45 \Omega \text{ cm}^2$ and $-0.73 \Omega \text{ cm}^2$, respectively. This indicates that through-plane electrical resistance is higher for the 7.4 mm RVC foam fuel cell, resulting from longer electron pathway through the RVC foam to the active sites for electrochemical reaction. Furthermore, increasing the RVC foam thickness, which is equivalent to increasing diameter of a pipe on a fluid flow system, facilitates gas bypassing effect, which hinders effective access of the reactant gas to the active sites of the catalyst layer, reducing fuel utilization efficiency [39,40]. Further improvement by employing thinner RVC foam with increased electrical conductivity can probably reduce internal ohmic resistance and shift the polarization curve upward for better fuel cell performance.

3.5. Effect of operating pressure on the cell performance

Experiments were conducted on a single RVC foam fuel cell built with a piece of 80PPI RVC foam at a thickness of 5.0 mm under various operating gauge pressures (0, 35, and 80 kPa) to establish the effect of operating pressure on the cell performance. It was experimentally proven that the cell performance improves as the

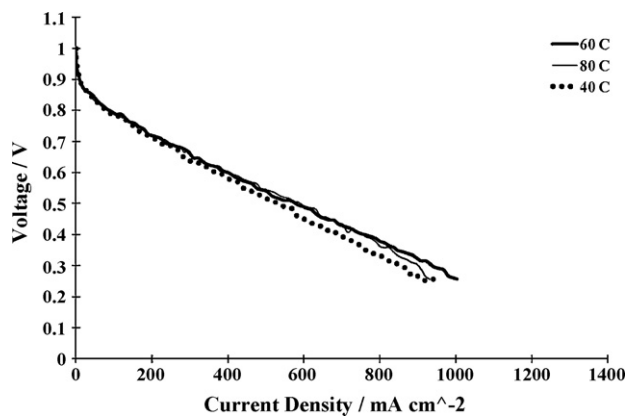


Fig. 9. Effect of the operating temperature on the cell performance (operating gauge pressure: 35 kPa/35 kPa, operating temperature: 40, 60, and 80 °C, relative humidity: 100%/100%, stoichiometric ratio: 1.4/3.0 for anode/cathode).

operating gauge pressure increases. At higher operating pressure, a greater number of molecules of the reactant gases are introduced for electrochemical reaction at the active sites according to the ideal gas law presented in Eq. (4). The cell operating at 0 kPa and 80 kPa produces a current density of 415 mA cm⁻² and 502 mA cm⁻² at 0.6 V, respectively and 754 mA cm⁻² and 910 mA cm⁻² at 0.4 V, respectively. The rate of increase in the cell performance at higher operating pressure is steady as the load increases. In addition, operating the cell at higher pressure provides better stability in the cell voltage at high current densities. This states that the operational stability increases as the operating pressure increases. Furthermore, it should be noted that the RVC foam fuel cell is capable of producing a decent amount of power even at very low operating pressure—one of the advantages that the foam fuel cell design possesses.

3.6. Effect of operating temperature on the cell performance

Experiments were conducted on a single RVC foam fuel cell constructed with a piece of 80PPI RVC foam at a thickness of 5.0 mm to investigate the effect of operating temperature on the cell performance. The operating temperature was varied from 40 °C to 80 °C at intervals of 20 °C. It was ensured that the reactant gases were fully humidified at 100% relative humidity by keeping the humidification temperature equal to the inlet gas temperature; therefore, temperature change is the main effect determining the cell performance. Fig. 9 shows that the cell performance slightly improves as the operating temperature increases from 40 °C to 60 °C; however, as it further increases to 80 °C, the cell performance declines at higher current densities. Operating a PEMFC at high temperature improves ionic conductivity of hydrogen protons through the Nafion® membrane, increases limiting current density, and brings fast catalytic activity and high capacity for water removal by evaporation [21,25,41]. However, Nafion® membrane dehydration in the anode may occur at excessively high temperature, which would deteriorate the cell performance at high current densities. Furthermore, it should be noted that the RVC foam fuel cell is capable of generating a decent amount of power even at low operating temperature—one of the advantages that the foam fuel cell design possesses.

3.7. Effect of air flow rate on the cell performance

Experiments were performed on a single RVC foam fuel cell constructed with a piece of 80PPI RVC foam at a thickness of 5.0 mm to establish the effect of stoichiometric ratio of air in the cath-

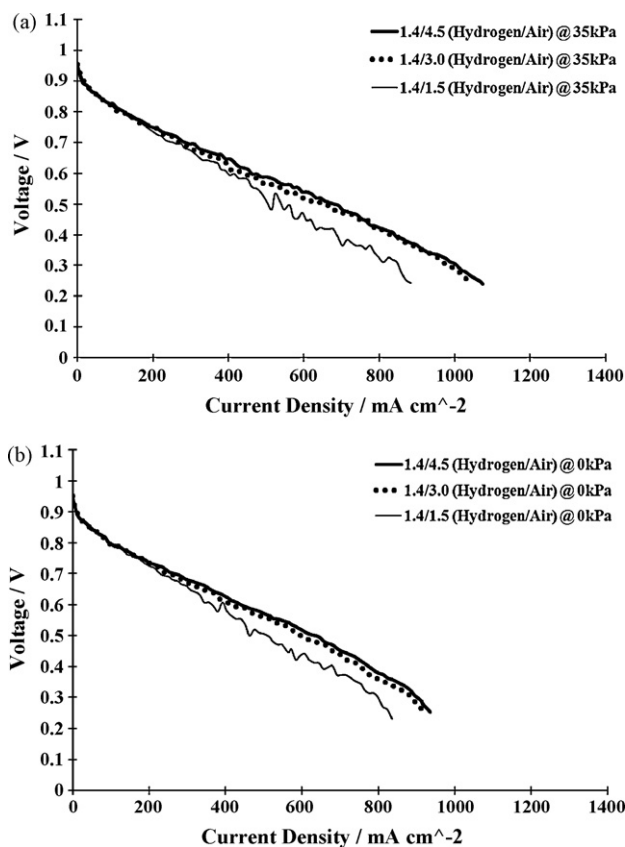


Fig. 10. Effect of the stoichiometric ratio of air in the cathode on the cell performance (operating gauge pressure: (a) 35 kPa/35 kPa and (b) 0 kPa/0 kPa, operating temperature: 60 °C/60 °C, relative humidity: 100%/100%, stoichiometric ratio: 1.4/1.5, 3.0, and 4.5 for anode/cathode).

ode on the cell performance. Stoichiometric ratio is the molar ratio between actual flow rate and theoretical flow rate of a reactant gas according to the reaction stoichiometry. The stoichiometric ratio of air in the cathode was varied from 1.5 to 4.5 at intervals of 1.5, but keeping that of hydrogen in the anode constant at 1.4. The effect of stoichiometric ratio of air on the cell performance is illustrated in Fig. 10. Operating gauge pressures of the inlet gas streams are set at 35 kPa and 0 kPa in (a) and (b), respectively. There is no significant difference in performance at various stoichiometric ratios of air at low current densities because sufficient amount of oxygen is provided for the electrochemical reaction and the oxygen consumption rate is low at high operating voltages. However, at medium and high current densities, as the stoichiometric ratio of air increases, not only the cell performance improves, but also the operational stability increases. A sudden drop in the slope of the polarization curve for the cell operating at the air stoichiometric ratio of 1.5 indicates that flooding effect might have taken place within the pore network of the RVC foam in the cathode side. At higher stoichiometric ratio, a larger amount of air is fed to the fuel cell, increasing oxygen concentration and reaction rate. Furthermore, high air flow rate helps remove product liquid water quickly and prevent from water flooding effect, thereby providing even distribution of local current density and reactant gas over the electrode.

It is interesting to note that the cell performance improvement from 1.5 to 3.0 is more pronounced than that from 3.0 to 4.5. For instance, at a current density of 500 mA cm⁻², the cell voltage increases from 0.51 V to 0.57 V and 0.57 V to 0.59 V as the cathode stoichiometric ratio changes from 1.5 to 3.0 and 3.0 to 4.5, respectively. Beyond the value of 3.0, the gain in the cell performance is almost negligible compared to the gain in the region

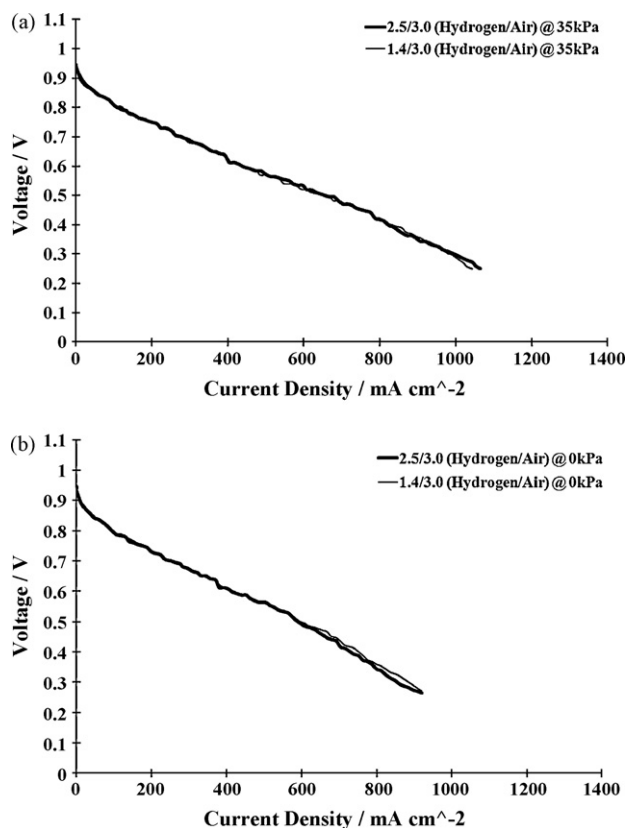


Fig. 11. Effect of the stoichiometric ratio of hydrogen in the anode on the cell performance (operating gauge pressure: (a) 35 kPa/35 kPa and (b) 0 kPa/0 kPa, operating temperature: 60 °C/60 °C, relative humidity: 100%/100%, stoichiometric ratio: 1.4 and 2.5/3.0 for anode/cathode).

below the value of 3.0. Therefore, it is not necessary to operate the RVC foam fuel cell at excessively high stoichiometric ratio of air to obtain the optimum PEMFC performance. Yan et al. [18] proved through experimental measurements that the cathode flow rate significantly influences the cell performance at high current densities because providing a large amount of oxygen to the active sites will enhance the electrochemical reaction and help remove liquid water; however, the rate of increase in the cell performance weakens as the cathode flow rate increases.

3.8. Effect of hydrogen flow rate on the cell performance

Experiments were performed on a single RVC foam fuel cell built with a piece of 80PPI RVC foam at a thickness of 5.0 mm to establish the effect of stoichiometric ratio of hydrogen in the anode on the cell performance. The stoichiometric ratio of hydrogen was varied from 1.4 to 2.5 while the stoichiometric ratio of air in the cathode was kept constant at 3.0. As shown in Fig. 11, for both cases at different operating gauge pressures, 35 kPa in (a) and 0 kPa in (b), varying the stoichiometric ratio of hydrogen gas does not have a significant impact on the cell performance when the inlet gas streams are fully humidified at 100% relative humidity. This is probably because the reaction rate of hydrogen oxidation is relatively fast and it is not a rate determining step.

3.9. Conclusions and recommendations

In the current study, a reproducible method for assembling a fuel cell using the Reticulated Vitreous Carbon (RVC) foam as a cathode flow-field has been described. A current density in excess of 1000 mA cm⁻² was obtained using the assembled RVC foam fuel

cell. Although the RVC foam fuel cell does not produce notably higher power density than the conventional fuel cell does, elimination of the highly expensive process of machining thin channels on graphite plates and reduction of cell weight and complexity have been achieved by employing the RVC foam in the cathode flow-field.

Furthermore, it has been proven through a parametric study that geometrical and material parameters of the RVC foam such as pores per linear inch (PPI) and thickness and operating conditions such as pressure, temperature, and stoichiometric ratio of the reactant gases significantly determine the performance of the RVC foam fuel cell, which highlights the importance of having a good understanding of the impact of those variables on the cell potential to reduce the polarizations.

Finally, it should be noted that the PEMFC made using the RVC foam on the cathode appears to possess an acceptable level of performance even when the operating pressure is kept close to atmospheric pressure and the operating temperature is relatively low compared to the typical operating conditions for the conventional fuel cell and that flooding appears to be controlled even when the humidity level of the incoming gases is kept very high at 100% relative humidity. This should result in a PEMFC that would be of great interest to various fuel cell manufacturers.

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