

Scaling up of the hybrid direct carbon fuel cell technology



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ABSTRACT

A hybrid direct carbon fuel cell (HDCFC), combining molten carbonate fuel cell (MCFC) and solid oxide fuel cell (SOFC) technologies, is capable of converting solid carbon directly into electrical energy without intermediate reforming. The performance level achieved on small-scale cells (area <4 cm²) suggests that engineering developments should now be undertaken to scale up and demonstrate the feasibility of practical systems. The scaling up of the HDCFC through the design and test of single stack repeat unit with realistic cell sizes was investigated in this study. A single cell of ~12.56 cm² active area produced a maximum power of ~1.2 W at 800 °C and a current density of ~200 mA cm² at 0.6 V, using woodbased pyrolyzed medium density fiberboard (p-MDF) as fuel. In comparison, the HDCFC with activated carbon as fuel produced a maximum power density of 36 and 53 mW $\rm cm^{-2}$ at 700 and 800 °C, respectively, and an electric efficiency of \sim 40% evaluated under 0.7 V for 17 h at 700 °C. These results demonstrated the applicability of HDCFC to practical systems while stack units were operated in batch mode and an appropriate fuel feeding mechanism has to be designed. Moreover, more engineering advances should be done to enhance power output since a HDCFC stack unit involves multiple challenges that have not been addressed yet, including system configuration and corrosion protection, and durability. Copyright © 2012, Hydrogen Energy Publications, LLC. Published by Elsevier Ltd. All rights

1. Introduction

The reliance on carbonaceous solid fuels to fulfill our growing energy needs will remain significant in the near future. Coal is the main energy source in the world and its share of world energy consumption is bound to 27% in this decade [1]. Other solid carbon sources include petroleum coke, pyrolytic carbon, biomass, and municipal carbon waste such as medium density fiberboard (MDF). Among them, the MDF is produced from discarded household wooden furniture with more than 20 million cubic meters per year [2]. Hence, how to make good use of this resource should be investigated. Currently, the methods for converting solid carbon fuels to electricity suffer from low efficiencies due to thermodynamic limitations and heat loss in the current centralized electricity production system. Therefore, the development of technologies for converting carbon to electricity with improved efficiency and scalability is highly desirable.

The direct carbon fuel cell (DCFC) has gained significant interest to generate power from solid carbon electrochemically [3–7]. In principle, such fuel cells generate electricity with a thermodynamic efficiency nearly 100%, compared with 30–40% for the combustion process in coal-fired power plant. Furthermore, the fuel cells that separate oxidant (e.g. O^{2-} or CO_3^{2-}) and air allow to suppress NO_x production and can sequestrate the main product, CO_2 , in a concentrated form for better air control. Other advantages such as scalability and quiet operation have a valuable diversity in stationary applications.

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Various concepts have since been proposed to develop DCFCs using molten salts [8–11] and solid oxide electrolytes [12–17]. The first type of DCFC was developed based on molten salt of alkali hydroxides, while the hydroxide is subject to degradation due to reaction with carbon dioxide. Replacement of hydroxide with carbonate salts overcomes the electrolyte degradation. Nevertheless, both hydroxide and carbonate molten salt corrode the components of fuel cell and pose difficult cell assembly. The solid electrolyte based DCFC provides the advantage of assembly and process simplicity. However, the performance of solid-electrolyte based DCFC (DC-SOFC) is limited because the contact for solid carbon, oxidant, and electronic conductor on the anode is confined. The OCVs obtained in DC-SOFCs differ from the theoretical value of carbon oxidation, i.e. 1.02 (volt), implying difficulties of direct oxidation [13,18–20].

Previous research in our group has focused on the development of hybrid direct carbon fuel cell (HDCFC) by combing advantages of molten salt and solid electrolyte fuel cells [18,21–23]. The HDCFC has a hybrid-state (molten and solid) electrode/electrolyte design, which increases the contact and cell performance by fluidity and mediation of molten salts [24–27] above solid electrolyte. As compared with molten carbonate fuel cells (MCFCs), the HDCFC avoids the CO₂ recirculation at the cathode; moreover, the introduction of the solid electrolyte protects the cathode from corrosion by the molten carbonates [4]. As compared to SOFCs, the introduction of the molten salt brings solid carbon to the interface of electrode/ electrolyte, thus extending reaction zone from two-dimension to three-dimension and improving the cell performance.

Important advances in the HDCFC technology have previously been reported with pyrolyzed medium density fiberboard (PMDF) and activated carbon fuels using planar button cells made of NiO/YSZ/YSZ/LSM materials and a eutectic lithium/potassium molten carbonate. The power densities of 50 and 394 mW cm⁻² were demonstrated using electrolytesupported cells and anode supported cells, respectively, with open circuit voltages (OCV) of 1.15–1.23 V [18,23,28]. While research is still underway to improve performance and to better understand underlying reaction mechanisms as well as best operating conditions, the level of performance achieved in our previous results suggests that parallel developments should now be undertaken to demonstrate the feasibility of scaling up for practical HDCFC stacks.

Here, we demonstrate the HDCFC technology in a single cell with a large surface area as first step in the path from button cells to cell stacks. The design and the performance of a HDCFC stack repeat unit using commercially available solid oxide cells is presented. Such a unit will be subsequently repeated to build up the system for power output. We will show that the hybrid DCFC is, indeed, important in applying the upcoming direct carbon fuel technologies to coal conversion and achieving high performance for continuous power generation.

2. Experimental section

2.1. Cell assembly and current collection

A circular anode-supported cell (HC Starck) with a diameter of 50 mm was used in this study. The cell consists of a porous

NiO/YSZ support layer (475–574 μ m), a dense 8YSZ electrolyte (5–10 μ m), a dense YDC layer (5–10 μ m), and a LSCF perovskite material (30–50 μ m). The NiO/YSZ layer is green with a diameter of 50 mm as an anode; the LSCF layer is black with a diameter of 40 mm as a cathode, shown in Fig. 1(a). Between the anode and cathode were sealed by one thermiculite ring gasket material (Thermiculite 866, Flexitallic) (I.D. = 50 mm, same as the cell size) to prevent gas from crossover as shown in Fig. 1(b).

The current collection was built with two strips of nickel mesh: one attached on the anode and the other attached on the cathode by silver paste. Two strips of nickel meshes were insulated by the previously mentioned thermiculite and fixed by another thermiculite ring (I.D. 40 mm, same as the cathode size) both on two electrodes, so short circuit can be avoided. The thermiculite material is chemically and thermally stable; in addition, the material is not degraded by the carbonates, thus allowing for efficient sealing and electrical insulation.

2.2. Cell testing and carbon/carbonate mixture

Fig. 2(a) shows the stack repeat unit for cell testing, consisting of an anode and cathode chamber made of stainless steel 316L. The cathode chamber features a gas flowing pattern machined onto the steel surface to allow for air flow. The anode chamber features a large cylindrical chamber that accommodates the carbon/carbonate mixture. The assembly of fuel cell with sealing and current collection was placed between two chambers, which was aligned and tightened by the screw through four holes machined throughout two chambers. The practical configuration after assemblage is depicted on Fig. 2(b).

The testing chamber was then placed in the furnace and heated to designed temperatures prior to performance



Fig. 1 – (a) An anode supported cell, (b) Seal with thermiculite and current collection.

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