Renewable and Sustainable Energy Reviews 65 (2016) 961–977

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

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

A review on unitized regenerative fuel cell technologies, part-A: Unitized regenerative proton exchange membrane fuel cells

Yifei Wang [a], Dennis Y.C. Leung [a,*], Jin Xuan [a,b], Huizhi Wang [a,b]

[a] Department of Mechanical Engineering, The University of Hong Kong, Pokfulam Road, Hong Kong
[b] School of Engineering & Physical Sciences, Heriot-Watt University, Edinburgh EH14 4AS, United Kingdom

A R T I C L E I N F O

Article history:
Received 17 November 2015
Received in revised form
21 June 2016
Accepted 8 July 2016

Keywords:
Unitized regenerative fuel cell
Proton exchange membrane
Bifunctional catalyst
Gas diffusion layer
Bipolar plates
Practical applications

A B S T R A C T

Energy storage and conversion is a very important link between the steps of energy production and energy consumption. Traditional fossil fuels are natural and unsustainable energy storage medium with limited reserves and notorious pollution problems, therefore demanding for a better choice to store and utilize the green and renewable energies in the future. Unitized regenerative fuel cell (URFC), a compact version of regenerative fuel cell with only one electrochemical cell, is one of the competent technologies for this purpose. A URFC can produce hydrogen fuel through an electrolysis mode to store the excess energy, and output power in a fuel cell mode to meet different consumption requirements. Such a reversible system possesses several distinctive advantages such as high specific energy, pollution-free, and most importantly, the decoupled energy storage capacity with rated power. Based on the different electrolytes utilized, current available URFC technologies include the most common proton exchange membrane (PEM)-based URFC, and other types of URFC such as the alkaline, solid oxide and microfluidic URFCs. This part of the URFC review emphasizes on the PEM-based URFC. Specifically, the research progress on both cell components and systematic issues is introduced. Benefiting from its fairly mature technology stage, the PEM-based URFC has already been applied in aerospace and terrestrial areas. However, for large-scale application, their cost and efficiency are still the obstacles when competing with other energy storage technologies. As for the alkaline, solid oxide and microfluidic types of URFC, their research progress is reported independently in part B of this review.

Contents

Abbreviations: ATO, Sb-doped SnO_2; BHC, Bifunctional hydrogen catalyst; BOC, Bifunctional oxygen catalyst; BOP, Balance of plant; BPPs, Bipolar plates; EC, Electrolysis cell; FC, Fuel cell; GDB, Gas diffusion backing; GDE, Gas diffusion electrode; GDL, Gas diffusion layer; HER, Hydrogen evolution reaction; HOR, Hydrogen oxidation reaction; LLNL, Lawrence Livermore National Laboratory; MEA, Membrane electrode assembly; MH, Metal hydride; MPL, Microporous layer; OER, Oxygen evolution reaction; ORR, Oxygen reduction reaction; PEM, Proton exchange membrane; PEMEC, Proton exchange membrane electrolyzer cell; PEMFC, Proton exchange membrane fuel cell; PPD, Peak power density; PV, Photovoltaic; RFC, Regenerative fuel cell; RFB, Redox flow battery; R-PEMFC, Regenerative proton exchange membrane fuel cell; UPS, Uninterrupted power supply; URFC, Unitized regenerative fuel cell; UR-PEMFC, Unitized regenerative proton exchange membrane fuel cell; UR-AFC, Unitized regenerative alkaline fuel cell; UR-SOFC, Utilized regenerative solid oxide fuel cell; UR-MFC, Utilized regenerative microfluidic fuel cell; ZEV, Zero-emission vehicles

* Corresponding author.
E-mail address: ycleung@hku.hk (D.Y.C. Leung).

http://dx.doi.org/10.1016/j.rser.2016.07.046
1364-0321/

1. Introduction

Nowadays environmental issues, such as global climate change and air pollution, have strongly attracted world's attention. Traditional fossil fuels are still the predominant energy source for human activity, which are responsible for many well-known environmental problems, typically the global warming due to massive CO_2 emissions and the air pollution due to the emissions of SO_x and NO_x. In addition, fossil fuel reserves are limited. According to a prediction in 2009, coal can last for about 107 years, crude oil for about 35 years, and nature gas for about 37 years [1], while world population and energy demand still keep increasing. When facing these problems, either the optimization of existing fossil fuel utilization facilities or the development of renewable energy sources is promising, of which the latter one is more sustainable considering the limited reserve of fossil fuels. Renewable energies such as solar, wind, geothermal etc. are getting more and more attention and investment in recent years, with a growing capacity and proportion in world energy supply. However, the intermittent nature of renewable energies has restrained their application prospect. In order to balance with their energy production intermittency, either secondary batteries or regenerative fuel cells (RFC) are proposed as auxiliary energy storage & conversion component for them.

As shown in Fig. 1(a), a RFC is composed of three main parts: a fuel cell for power generation, an electrolysis cell for fuel production, and a fuel storage component. In addition, an oxygen storage part can also be added for a completely-closed RFC system. When coupled with renewable power sources, the electrolyzer can utilize the redundant and inferior power input to split water for hydrogen generation, while during the power output period hydrogen fuel will flow back to fuel cell and output stable electric power. To make a more compact system, the fuel cell part and the electrolyzer part can be unitized into a single electrochemical cell, which functions alternatively as fuel cell and electrolyzer, as shown in Fig. 1(b). This unitized regenerative fuel cell (URFC) holds several advantages against the conventional discrete RFC, such as lower capital cost, simpler structure, higher specific energy, no need for auxiliary heating [2], etc.

Till now, secondary batteries are widely used for energy storage purpose due to their high round-trip efficiency (around 80%) [3], but their drawbacks are also evident. The durability of secondary batteries is not very satisfactory when facing deep cycling, and their specific energy is constrained by the heavy weight. Moreover, the coupling of energy storage capacity and rated power has made secondary batteries less efficient to scale up. To solve this problem, redox flow batteries (RFBs) are proposed as an alternative choice. Unlike the conventional secondary batteries which store reactants within the cell, the RFBs utilize electro-chemical reactants dissolved in electrolytic solutions which are stored in external tanks and circulated on the electrode surface during operation. In this way, the energy storage capacity and rated power of RFBs are decoupled [4]. By enlarging the electrolyte storage tank the capacity can be easily increased, while the rated power can be enhanced by enlarging the electrodes' area or through stacking. However, due to the bulk electrolyte solution contained in the system, the specific energy of RFBs is generally much lower. Similar to RFBs, URFCs also store the fuel and oxidant, generally H_2 and O_2, externally in separated gas tanks, therefore achieving decoupled storage capacity and output power, but their specific energy is much higher due to the absence of liquid electrolyte, which is about 0.4–1.0 kWh kg^{-1} including the mass of the hydrogen and oxygen gas tanks [5]. In addition, URFCs can be totally charged and discharged without damaging the durability compared with secondary batteries. These advantages have made URFCs very competitive against secondary batteries and RFBs. However, URFCs generally achieve lower round-trip efficiency than batteries due to the sluggish oxygen reactions. Other issues such as high cost, hydrogen storage, and relatively low technology readiness, have also hindered their applications.

Same as the classification of fuel cells, URFCs can also be classified by the electrolytes they employ, such as the unitized regenerative proton exchange membrane fuel cell (UR-PEMFC),

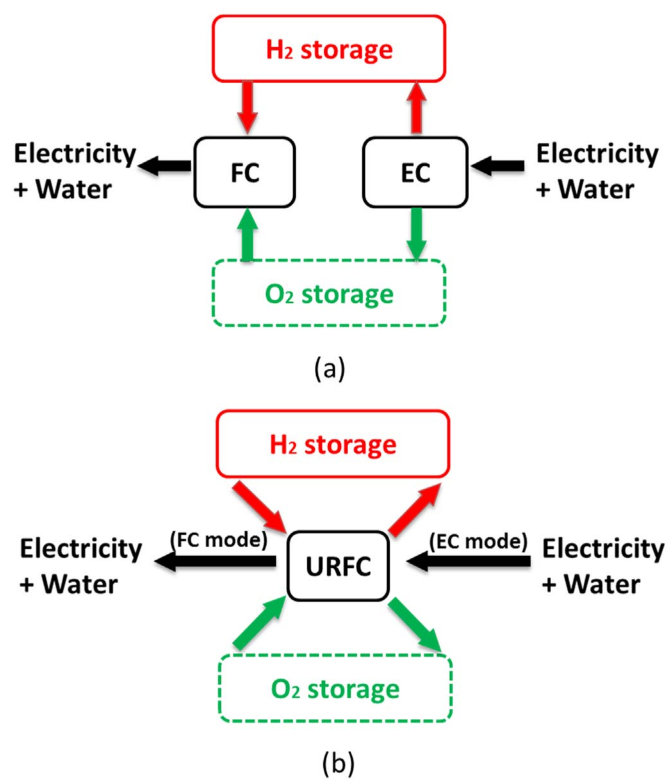

Fig. 1. Comparison between RFC and URFC: (a) RFC; (b) URFC.