Composite Structures 159 (2017) 220–227

Contents lists available at ScienceDirect

Composite Structures

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

Nano carbon/fluoroelastomer composite bipolar plate for a vanadium redox flow battery (VRFB)

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ARTICLE INFO

Article history:
Received 20 September 2016
Accepted 22 September 2016
Available online 23 September 2016

Keywords:
Vanadium redox flow battery
Bipolar plate
Fluoroelastomer composite
Soft-layer method
Electrical conductivity

ABSTRACT

The energy storage system (ESS) is widely investigated because it can solve various energy-related problems without additional power plants. Among the ESSs, a vanadium redox flow battery (VRFB) is one of the most promising technologies due to its scalability without explosiveness. The bipolar plate is a multifunctional component that provides an electrical path and separates cells. A bipolar plate should simultaneously have low electrical resistance, high mechanical properties and chemical durability.

In this study, a nano carbon/fluoroelastomer composite bipolar plate was developed to substitute for the conventional thick graphite bipolar plate. The 'soft-layer method' was adopted to expose the carbon fibers on the surface of the composite to increase its electrical conductivity. The solution casting method was applied to fabricate the high fiber volume fraction composite structure with a dispersion of carbon black. The performance of the carbon/fluoroelastomer composite bipolar plate was evaluated by testing the permeability, mechanical properties, and electrical properties. Finally, unit-cell charge/discharge tests were conducted to verify the performance of the composite bipolar plate.

1. Introduction

The energy storage system (ESS) is widely investigated throughout the world because it can solve the various energy-related problems such as sudden black outs and it can be applied with a renewable energy system to provide a stable power supply [1–3]. In addition, efficient electrical energy management is possible with an ESS by leveling the electricity load. The vanadium redox flow battery (VRFB) is one of the most promising ESSs, along with lithium batteries [4]. The VRFB has various advantages over lithium batteries with respect to safety and scalability [5]. Because the VRFB is not explosive regardless of its size, it is more desirable for large-scale battery systems. In addition, the VRFB can be scaled-up easily because the electrical power and capacity can be designed independently.

The VRFB is operated by the flow of electrolytes as shown in Fig. 1, and it stores electrical energy by the potential difference between the positive and negative electrolytes when it is charged. The electrolytes are prepared from a vanadyl sulfate solution that consists of vanadium oxide and sulfuric acid [6]. The unit-cell of a VRFB is typically composed of current collectors, bipolar plates, flow frames, a membrane, electrodes and gaskets as illustrated in Fig. 2. The flow frame is a supporting component, which provides the flow channel for the electrolytes. The membrane is a component that selectively transfers protons. The bipolar plate is a multifunctional component that provides the electrical current path, supports the structures and endures an electrochemically corrosive environment [7].

Conventionally, a graphite-based plate has been used as the bipolar plate for VRFBs because it has high electrical conductivity and chemical stability [4]. However, graphite is very brittle and has low mechanical properties. Therefore, it must be handled with great care during the assembly process and must be sufficiently thick, greatly increasing the production cost. Recently, an expanded graphite-coated carbon/epoxy composite bipolar plate has been developed to overcome the problems associated with the conventional graphite-based bipolar plate [8,9]. The expanded graphite-coated composite bipolar plate possessed high mechanical properties as well as high electrical conductivity. However, the coating process of the expanded graphite bipolar plate for large-scale production greatly increases the cost. In addition, Choe et al. investigated the chemical durability of this plate and reported that the expanded graphite coating could be damaged by the highly corrosive electrolytes after long operation cycles, especially with high current densities [10,11]. To solve these problems, Lee

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http://dx.doi.org/10.1016/j.compstruct.2016.09.063
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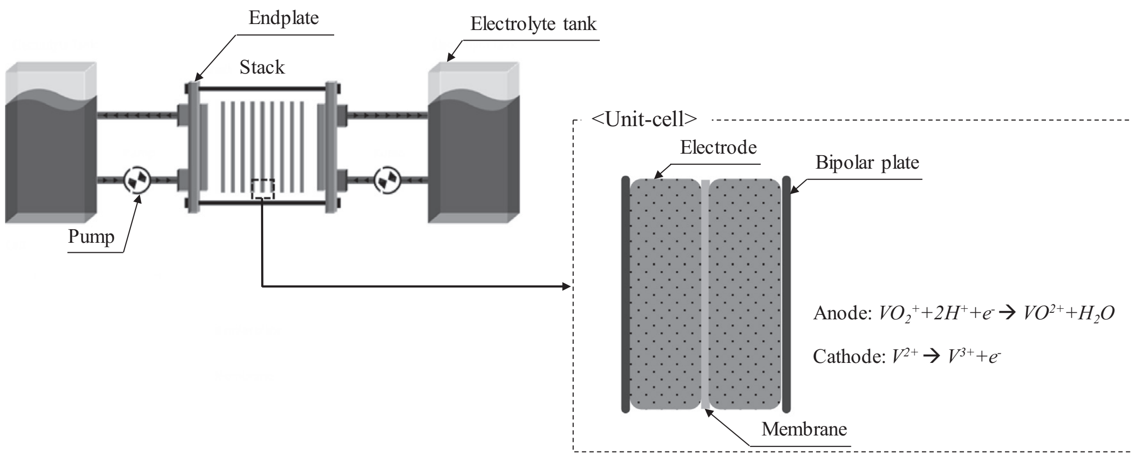

Fig. 1. Schematic diagram of a typical VRFB system and its chemical reactions in the unit-cell.

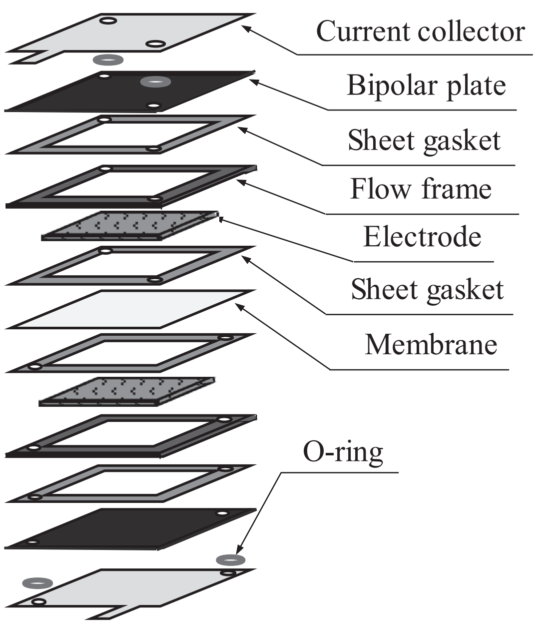

Fig. 2. Schematic diagram for components of a conventional VRFB unit-cell.

et al. developed the ‘soft-layer method’ that exposes the carbon fibers on the surface of the carbon/epoxy composite to increase the electrical conductivity without a conductive coating for a fuel cell application [12]. The bipolar plate produced by this ‘soft-layer method’ showed comparable performance to that of the expanded graphite coated bipolar plate. However, because the electrolyte for the VRFB has high a reduction potential and high acidity, the epoxy-based bipolar plate may be damaged under both oxidizing and acidic environments.

In this study, a nano-particle embedded carbon fiber/fluoroelastomer composite bipolar plate was developed to substitute for the previously developed bipolar plates for VRFBs. To achieve a high electrical conductivity, a fiber-exposing method, the so-called ‘soft-layer method’ was adopted from the previous study. In addition, a fluoroelastomer was adopted for the matrix because it has high chemical stability under both oxidizing and acidic environments. The composite structure should have a high fiber volume fraction to achieve a high electrical conductivity. Therefore, fabrication methods were investigated to increase the fiber volume fraction using the fluoroelastomer, including embedding conductive nano-particles. The permeability, mechanical properties and electrical properties of the nano carbon/fluoroelastomer composite bipolar plate were measured and evaluated with respect to the wt% of embedded nano-particles. Finally, the charge/discharge unit-cell test was performed, and the results were compared with those of the conventional graphite bipolar plate.

2. Fabrication of nano carbon/fluoroelastomer composites

2.1. Materials selection

The bipolar plate for a VRFB should have high electrical conductivity, mechanical properties and chemical stability. To achieve these multifunctional requirements of the bipolar plate for a VRFB, a nano carbon/fluoroelastomer composite structure was developed. A 0.12-mm-thick plain weave carbon fiber fabric (WSN 1k, SK Chemicals, Korea) was used for reinforcement to simultaneously achieve electrical conductivity and high mechanical properties. The fluoroelastomer was selected because it has a high chemical stability under both oxidizing and acidic environments [13]. For the fabrication of the composite structure, a fluoroelastomer compound (Dai-El G327, Daikin, Japan) composed of a fluoroelastomer and curing agents such as bisphenol and metal oxides (magnesium oxide and calcium hydroxide) without additional fillers which can increase the viscosity of compound, was prepared. Because the fluoroelastomer is an electrically insulating material, electrically conductive nano-size carbon black (Ketjen black 600JD, Mitsubishi Chemical, Japan) whose properties are listed in Table 1, was embedded in the fluoroelastomer resin during composite preparation to increase the electrical conductivity.

2.2. Fabrication method

A fluoroelastomer composite can generally be fabricated by 2 methods: a melt compounding method using a hot-press or a solution casting method using a solvent such as acetone or methyl

Table 1
Properties of the carbon black (Ketjen black EC-600JD).

Property	Value
Apparent bulk density	115 g/l
Ash content	0.1%
Surface area bet	1270 m^2/l
Iodine adsorption	1050 mg/g
DBP adsorption	495 (15 g method)