Review

Corrugated carbon/epoxy composite bipolar plate for vanadium redox flow batteries

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ARTICLE INFO

ABSTRACT

As the consumption of electricity has increased continuously, risk management of power outages has become an important issue. Energy storage systems have been proposed as a solution, which efficiently manage electricity by storing it during non-peak time and subsequently providing it during peak time. The vanadium redox flow battery (VRFB) is one of the safest and most durable energy storage systems, due to its unlimited capacity and non-flammability without explosion in comparison to other energy storage systems. However, the efficiency of the VRFB largely depends on the performance of bipolar plates (BPs), especially the shape of the BPs, which affects the flow of electrolyte and the surface area of electrodes. Therefore, optimizing the shape of the BPs for VRFBs is necessary.

In this study, a corrugated carbon/epoxy composite bipolar plate (CCBP) for VRFBs was designed to increase the efficiency of the electrolyte flow and decrease the area-specific resistance (ASR) of the CCBP. The shape of the corrugations in the CCBP was optimized to decrease both the ohmic and pumping losses in the VRFB stack. Finally, the designed CCBP was developed and tested by the ASR measurement and electrolyte flow.

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1. Introduction

The vanadium redox flow battery (VRFB) is a promising energy storage system, which enables excess electricity to be stored during non-peak time (night time and holidays) and subsequently delivered during peak time [1,2]. Furthermore, the VRFB has the advantages of unlimited power and energy capacities, non-explosive nature, and a long lifetime because the power capacity is determined by the stack size and stack numbers, while the energy capacity is determined by the amount of the electrolyte [3]. VRFBs store and supply electricity through reduction and oxidation reactions of vanadium ions. In a cathode, the VRFB reaction is as follows [4]:

$$VO_2^+ + 2H^+ + e^- \leftrightarrow VO^{2+} + H_2O \tag{1}$$
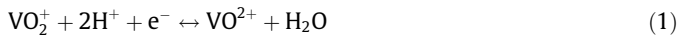
In an anode, the VRFB reaction is as follows:

$$V^{2+} \leftrightarrow V^{3+} + e^- \tag{2}$$

When the battery is discharging, V^{5+} ions (VO_2^+) in the catholyte are reduced to V^{4+} ions (VO^{2+}), and V^{2+} ions in the anolyte are oxidized to V^{3+} ions. These cathodic and anodic reactions occur in the electrodes simultaneously [4].

As shown in Fig. 1(a), a typical VRFB system is composed of a stack, two pumps, and two electrolyte tanks. The stack of a VRFB system consists of multiple unit cells, and a unit cell is composed of electrodes, a membrane, a flow frame, and bipolar plates (BPs), as shown in Fig. 1(b). In general, carbon felt is used as the electrode material, which provides reactive sites and an electrical path. The membrane provides a path for protons, and it separates half cells. The unit cell is separated by BPs, which should possess high electrical conductivity and high strength for their functional requirements [4,5].

Although the VRFB appears to have a structure similar to that of proton exchange membrane fuel cells, unlike fuel cells, the chemical reaction occurs in the liquid electrolyte and energy is stored there. Therefore, the properties of the electrolytes, such as concentration, amount, and composition, highly affect the performance of a VRFB system. There have been several attempts to optimize the properties of electrolytes to increase the energy density and efficiency [6–9]. However, even if the performance of the electrolytes is improved, energy loss in the VRFB is another issue that must be overcome to maximize the performance of the system. Due to the highly viscous nature of the electrolytes, a large amount of pumping loss occurs in a stack during operation. In general, the loss occurs when the electrolyte passes through the electrode, which is a porous material such as carbon fiber felt or mat [4]. It has been reported that approximately 10% to 15% of the total amount of energy produced is consumed as pumping loss. Furthermore, due to the electrical resistance of the stack components, ohmic losses occur in the electrodes, BPs, and current collectors, which decrease the efficiency of the VRFB system. When the battery is charged or discharged, some of the electrical energy is dissipated as thermal energy, which may degrade the properties of the electrolytes; some vanadium ions are precipitated when the temperature of the vanadium electrolyte is high [6]. Therefore, to increase the efficiency of the VRFB stack, it is important to minimize both the pumping and ohmic losses by the optimization of BP structures.

Hwang et al. developed a carbon/epoxy composite BP for the proton exchange membrane fuel cell, where a composite BP with a high modulus and strength was designed, and its performance was verified [10]. In addition to its superior mechanical properties, this composite BP possessed other advantages: high chemical resistance, high conductivity, low cost, and moldability [11]. Therefore, it is plausible to apply this BP in the VRFB system, and Kim et al. developed a carbon composite BP for the VRFB [3]. Although the developed composite BP has shown great performance, there are still possibilities for improving the overall stack performance by minimizing the losses that occur in the stack.

In this study, a corrugated carbon/epoxy composite BP (CCBP) for VRFBs was developed to increase the efficiency by decreasing pumping loss of electrolyte related to permeability of electrode, and reducing the area-specific resistance (ASR) relevant to ohmic losses. The permeability and ASR of carbon felt electrodes were measured with respect to their fiber contents. Then, the permeability and ASR of the electrodes were numerically calculated as a function of the corrugation shape, from which the pumping and ohmic losses were estimated. An optimum corrugation design was selected, and the performance of the designed CCBP was analyzed through ASR measurements and flow tests.

2. Design of the corrugation of the BP

A large amount of ohmic and pumping losses occur in the carbon felt electrode in the VRFB stack [4,6,12]. In the carbon felt electrode, highly conductive carbon fibers are randomly distributed and contact each other. Therefore, increasing the fiber content may decrease the electrical resistance, thereby reducing the ohmic loss. However, the carbon felt generally has low permeability due to the small fiber diameter of 7 μm, and it has a large ratio of surface area to volume that increases the drag force and decreases the permeability. Hence, if the fiber content is increased to decrease the ohmic loss, it may simultaneously increase the pumping loss in a stack. Therefore, using the carbon felt for the electrode in the VRFB stack is a coupled design, and it has to be decoupled.

The purpose of the CCBP is to provide electrode areas with both high and low fiber volume fractions, as shown in Fig. 2. In a high fiber volume fraction area, the electrical resistance is low, which will provide electron paths, and consequently reduce the total resistance of the electrodes. In contrast, a low fiber volume fraction area will provide an electrolyte path and significantly decrease the pumping loss. Because the electrical resistance and the permeability of fabric materials generally change exponentially in terms of the fiber volume fraction, it has been hypothesized that the non-uniform compression of the carbon fiber electrode by the CCBP may exhibit a synergistic effect for decreasing losses [13,14]. To verify this hypothesis, the ASR and permeability were measured experimentally with respect to the fiber volume fraction of carbon felt. Then, the ohmic and pumping losses were numerically calculated to determine the corrugation shape as a function of the shape of corrugations of the CCBP.

2.1. Electrical property measurements

The electrical resistance in the through-thickness direction of the carbon felt, i.e., the ASR, was measured as a function of the fiber volume fraction. The properties of the carbon felt are presented in Table 1. The specimen size was 100 mm by 100 mm, and the experimental equipment is shown in Fig. 3 [15]. The carbon felt specimen was placed between two gold-coated plates to reduce electrical contact resistance and compaction pressure was applied using a universal testing machine (INSTRON 4469, Instron Corp., MA, USA) at a temperature of 25 ± 1 °C with the crosshead speed of 1 mm/min. The fiber volume fraction of the carbon felt was increased up to 30%.

As shown in Fig. 4(a), the measured ASR was 350 mΩ cm² for the initial fiber volume fraction of 3.3% and 30 mΩ cm² for the fiber volume fraction of 30%. Furthermore, the resistance of the carbon felt exponentially decreased as the fiber volume fraction was increased because the resistance R is proportional to the electrical resistivity ρ of the material and the length l of the electrical path