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Smart cure cycle for reducing the thermal residual stress of a co-cured E-glass/carbon/epoxy composite structure for a vanadium redox flow battery

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A B S T R A C T

The vanadium redox flow battery (VRFB) is considered as one of the most promising energy storage system in the future. It is composed of two endplates and a stack which consists of flow frame (FF), electrode, bipolar plate (BP) and membrane. Because the electrolytes flowing in the stack are sulfuric-acid-based solutions, prevention of leakage is important. The unified structure of the FF and the BP manufactured by co-curing E-glass/epoxy and carbon/epoxy composites not only prevents leakage, but also simplifies assembling process. However, large thermal residual stress is induced due to the difference of coefficients of thermal expansion between E-glass/epoxy and carbon/epoxy composites.

In this work, smart cure cycle was developed to reduce the thermal residual stress of the co-cured E-glass/carbon/epoxy structure for VRFB. The deformations of structure fabricated using smart cure cycle were investigated with respect to the degree of cure and post-cure process using the viscoelastic properties of composite materials during post-cure process. In addition, the thermal residual stress and actual bonding temperature were calculated. Using the experimental results of degree of cure and actual bonding temperature, a finite element analysis was performed to verify the stress of the co-cured FF–BP structure as a function of the cure cycles.

1. Introduction

Secondary batteries have been developed as large-scale energy storage systems for backup systems in smart grids, power plants and renewable energy systems [1,2]. The vanadium redox flow battery (VRFB) is one of the most promising technologies alongside lithium batteries [1,3,4]. The VRFB is an attractive technology compared to lithium batteries because the VRFB is non-explosive. In addition, the electric power and capacity of the VRFB can be designed independently. The typical structure of a VRFB system is shown in Fig. 1 [5]. Two different types of liquid electrolytes (catholyte and anolyte) are delivered by the pumps into the stack, which is composed of several unit cells. In the unit cell, the electric power is generated and stored by electrochemical reactions between two electrolytes with four different oxidation states (VO^{2+}/VO_2^+ in the catholyte and V^{2+}/V^{3+} in the anolyte).

The stack of the VRFB consists of a number of unit cells, and each unit cell is composed of two bipolar plates, two electrodes, two flow frames and a membrane, as shown in Fig. 2(a). Conventionally, graphite is used as a material for the bipolar plate (BP), and polypropylene (PP) or polyvinyl chloride (PVC) is generally used for the flow frame (FF). The electrolytes are supplied through the flow frame and into the carbon fiber felt electrode at a pressure of 0.1–0.2 MPa. The electrolytes may leak out of the stack through the possible leakage paths shown in Fig. 2(b). The leakage of the electrolyte results in an unbalanced concentration between two electrolytes, which affects the reaction efficiency of the VRFB. Additionally, the leaked electrolyte can damage other components and the VRRB system because the electrolytes are high sulfuric-acid-based solutions [6,7]. Conventional VRFB systems use gaskets or O-rings to prevent leakage of the electrolytes. However, gaskets and O-rings produce problems in the construction of large-scale VRFB systems. First, a large number of gaskets or O-rings are required because a stack consists of tens or hundreds of unit cells, and each unit cell has many possible leakage paths between the components. Second, the electrolytes are acidic

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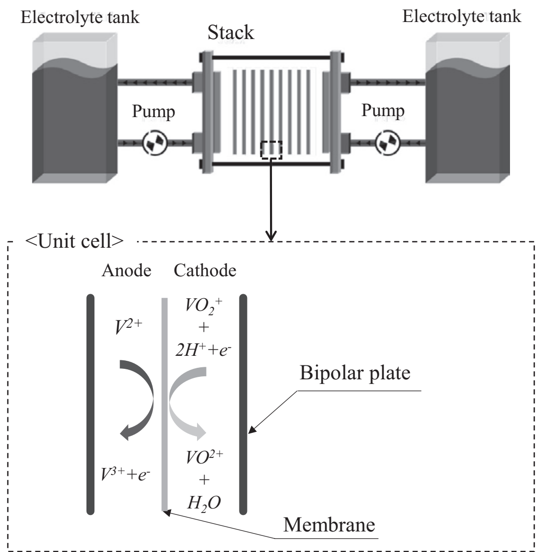

Fig. 1. Schematic diagram of a VRFB system and the chemical reactions in the unit cell.

solutions, which results in the need for expensive, acid-resistant materials for the gaskets and the O-rings. Additionally, assembling and aligning the components is complicated with a large number of gaskets or O-rings, and the fastening components would become loose during long-term operation (10–20 years), especially in large-scale VRFB systems [8–10].

In this study, the leakage problem was reduced much by co-cure bonding the E-glass/epoxy flow frame and the carbon/epoxy bipolar plate. The co-cure bonded flow frame–bipolar plate (FF–BP) structures for the middle and end cells are shown in Fig. 3. The co-cured FF–BP structure has several advantages for the VRFB system. First, the leakage path between the flow frame and the bipolar plate is completely removed because they are composed of the co-cure bonded structure. Second, the E-glass/epoxy composite flow frame and the carbon/epoxy composite bipolar plate can guarantee long-term reliability because they are chemically stable and have good mechanical properties compared conventional PP or PVC flow frames [11]. Third, the number of assembling components can be reduced by 70%, and the number of gaskets or O-rings can be reduced by 50% compared to that of the conventional VRFB stack.

Although the co-cured FF–BP structure has many advantages, it also exhibits some problems. Epoxy matrix based commercial

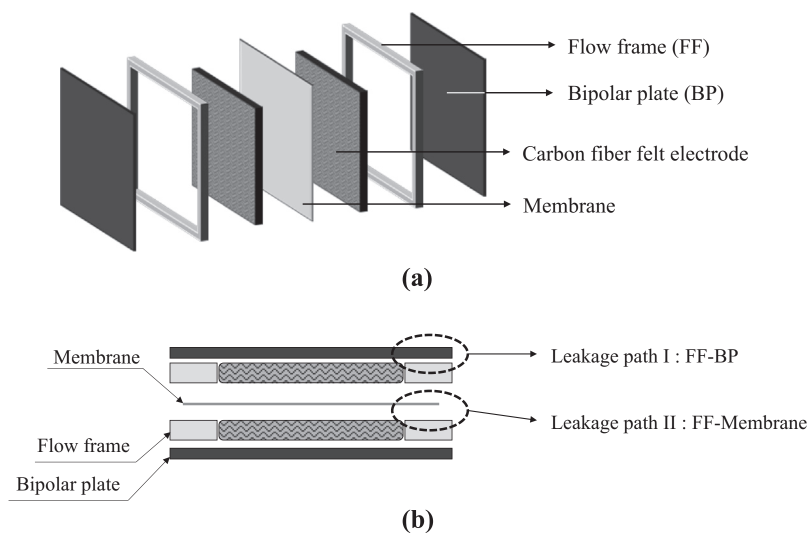

Fig. 2. Unit cell of the VRFB: (a) configuration of the components; (b) possible leakage paths between the components.

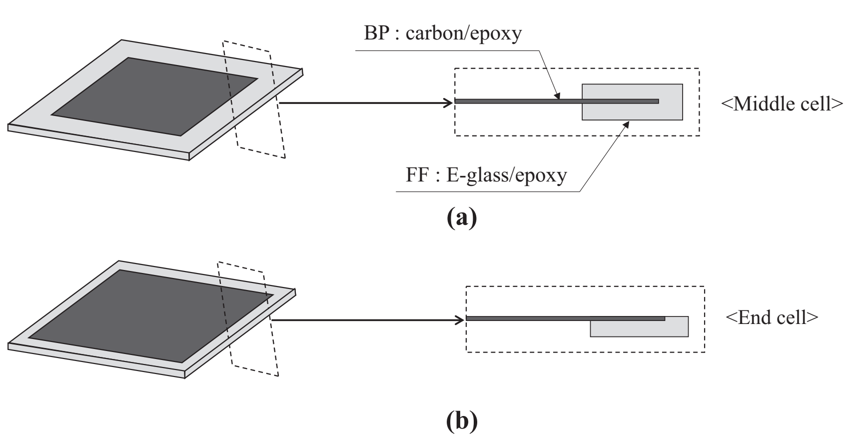

Fig. 3. Configurations of the co-cured FF–BP structure: (a) middle cell; (b) end cell.