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## Performance of the all-vanadium redox flow battery stack

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### ABSTRACT

The all-vanadium redox flow battery (VRFB) stack of a kW class, which was composed of 31 cells with an electrode surface area of 2714 cm<sup>2</sup> and a commercial anion exchange membrane, was tested using the electrolyte of 1.2 M VOSO<sub>4</sub> in 2 M H<sub>2</sub>SO<sub>4</sub>. The charge–discharge cycle performance of VRFB stack was measured at the current density of 60 and 90 mA cm<sup>-2</sup>. Average energy efficiencies during charge–discharge cycle in the VRFB stack were about 76% and 70% for the current density of 60 and 90 mA cm<sup>-2</sup>, respectively. It was confirmed from the tested data that the homemade VRFB stack is suitable for the electric storage with high efficiency. The input power (IP) and output power (OP) in the VRFB stack at 90 mA cm<sup>-2</sup> were 11.4 kW and 8.9 kW, respectively.

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### Introduction

Power systems using renewable energy such as a solar and wind are being actively investigated worldwide. A power system using renewable energy needs an energy storage system because of its low energy density and intermittent nature. The redox flow battery (RFB) is being investigated as an energy storage system for the load leveling and an emergency uninterruptable power supplies [1–3]. A RFB is able to store electrical energy in the form of chemical energy and convert that into electricity [4,5]. One advantage of a RFB is that the power and energy storage capacity can be increased easily. In particular, the all-vanadium redox flow battery (VRFB) is being investigated for this purpose [1–5].

In VRFB energy storage system, an ion exchange membrane (IEM) is widely used as a separator. An IEM should possess a low membrane resistance to minimize losses in voltage efficiency, and should exhibit low permeation rates of the vanadium ions (V<sup>2+</sup>, V<sup>3+</sup>, VO<sup>2+</sup>, VO<sub>2</sub><sup>+</sup>) through the membrane to minimize loss of the energy capacity caused by crossover of the vanadium ions. And, the IEM should also possess a good chemical stability and low cost [6,7]. Many researchers are being investigated an IEM to achieve those properties [8–19].

The energy storage capacity of VRFB which was using the VO<sup>2+</sup>/VO<sub>2</sub><sup>+</sup> and V<sup>3+</sup>/V<sup>2+</sup> redox couples in H<sub>2</sub>SO<sub>4</sub> aqueous solution for a positive and negative electrolytes, respectively, are dependent on the concentration and volume of the electrolytes. In VRFB, the low

energy density of the vanadium sulfate electrolyte is caused by the low solubility and stability of the active vanadium species at the elevated temperature. In particular, the precipitate formation in the pentavalent vanadium electrolyte (VO<sub>2</sub><sup>+</sup>) was occurred over the temperature of 40 °C [20]. Recently, it is being investigated to improve low solubility and stability of the electrolyte, and to prevent of the precipitate formation in pentavalent vanadium electrolyte by adding the stabilizing agents and an organic or inorganic additives [20–25].

The output power of VRFB is dependent on the number of unit cells and the surface areas of the electrodes [26]. The energy efficiency (EE) of VRFB is dependent on the physicochemical properties of the used electrodes because the electrochemical reactions of vanadium ions are occurred on the electrode surface. The graphite felt is mainly used as an electrode material in VRFB because it exhibits good stability in highly acidic solutions, and provides a large reactive surface area and a sufficient number of redox reaction sites [27]. The research for the modification of electrode materials is being conducted to enhance their electrochemical performance [28–33]. The power of VRFB is directly proportional to stack size which was connected to one another in either series or parallel of unit cells. The performance information of VRFB cell stack which was used the commercial component materials, needs to use its more application, and to improve its performance and cost.

In our previous paper, it was confirmed that a commercial anion exchange membrane had a good durability in the pentavalent vanadium ion solution, and the energy efficiency of VRFB showed almost the same value compared to that using Nafion117 [3].

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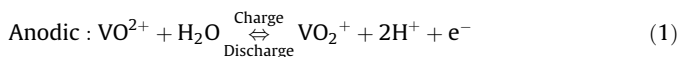
### Nomenclature

CE	Current efficiency, %
EE	Energy efficiency, %
$E_{AC}$ , $E_{AD}$	Average stack voltage for charge and discharge, respectively, V
$Q_C$ , $Q_D$	Quantity of the coulomb for charge and discharge, respectively, C
VE	Voltage efficiency, %

In this research, the electrochemical performance of VRFB (using an anion exchange membrane) stack composed of the 31 cells (about 10 kW class), was evaluated at the some current density. And the performance change of VRFB stack was measured for a great number of cycle.

### Experimental

The charge and discharge reactions in the VRFB are as follows:



As shown in Fig. 1, the VRFB stack was constructed according to the specifications in Table 1.

Aluminum end plates, bolts, and gold coated copper plates were used for structural support and electrical connection to the stack, respectively. A phenol resin impregnated carbon plate (8650, Ildo F&C Co., Korea) was used as a current collector. The carbon felt (XF30A, Toyobo Co., Japan) was used as a working electrode. An anion exchange membrane (AFN, Astom Co., Japan) was used as a separator in VRFB.

1.2 M  $\text{VOSO}_4$  in 2 M  $\text{H}_2\text{SO}_4$  ( $\text{VO}^{2+}$ ) aqueous solution was used as an anolyte and 1.2 M  $\text{VOSO}_4$  in 2 M  $\text{H}_2\text{SO}_4$  ( $\text{V}^{3+}$ ) aqueous solution which was an electrically reduced solution of anolyte was used as a catholyte.

The VRFB stack was composed of 31 cells with an electrode surface area of 2714  $\text{cm}^2$ , and overall stack dimensions were 622 (l)  $\times$  660 (w)  $\times$  657 (h) mm. The flow rate of the electrolyte was 1.0  $\text{mL min}^{-1} \text{cm}^{-2}$ . The electrochemical performance of stack was tested using a battery tester (BT 2000, Arbin Instruments Co., USA).



Fig. 1. Photo of VRFB stack with 31 cells.

Table 1

Specifications for VRFB stack.

Area of felt electrode	2714 $\text{cm}^2$ (59 $\times$ 46)
Number of cells	31
Membrane	AFN (Astom Co, Japan)
Bipolar plate	Graphite plate (3 mm)
Flow frame	PVC (polyvinyl chloride)
End plate	Aluminum alloy
Stack dimensions (L $\times$ W $\times$ H)	622 $\times$ 660 $\times$ 657 mm
Electrolyte	1.2 M $\text{VOSO}_4$ in 2 M $\text{H}_2\text{SO}_4$
Electrolyte volume per half-cell	30 L
Operation temperature	Ambient

The charge and discharge of stack was carried out between 1.6 and 1.0 V per cell, respectively, according to our previous paper [3]. The open circuit voltage (OCV) of the stack was measured by stopped charging and discharging at the several times.

The charge–discharge cycle test of the VRFB stack was carried out at the current density of 60 and 90  $\text{mA cm}^{-2}$ . The stack properties such as a current efficiency (CE), voltage efficiency (VE), and energy efficiency (EE) were calculated using Eqs. (3)–(5), respectively:

$$\text{CE} = Q_D/Q_C \quad (3)$$

$$\text{VE} = E_{AD}/E_{AC} \quad (4)$$

$$\text{EE} = \text{CE} \times \text{VE} \quad (5)$$

where  $Q_C$  and  $Q_D$  (C) are the quantity of the coulomb for charge and discharge, respectively, and  $E_{AC}$  and  $E_{AD}$  (V) are the average stack voltage for charge and discharge, respectively.

### Results and discussion

#### OCV and stack voltage of VRFB

Fig. 2 shows the open circuit voltage (OCV) and VRFB stack voltage at the current density of 60  $\text{mA cm}^{-2}$ .

In the VRFB stack tested at 60  $\text{mA cm}^{-2}$ , the open circuit voltage (OCV) increased from 36.5 V to 43.6 V with an increase of charge time, and that decreased from 35.7 V to 24.0 V with an increase of discharge time. The VRFB stack voltage increased from 42.5 V to 49.6 V with an increase of charge time, and that decreased from 41.8 V to 30.0 V with an increase of discharge time.

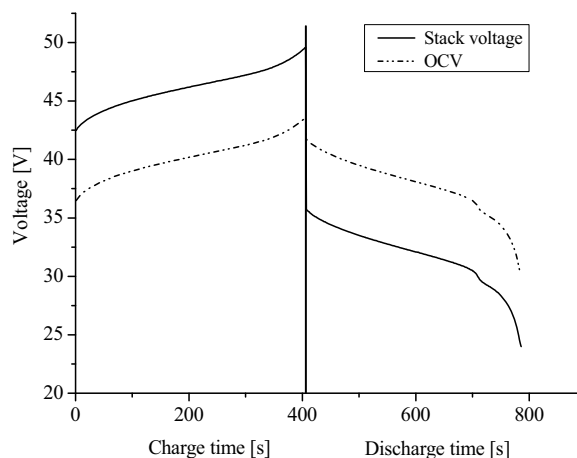


Fig. 2. Open circuit voltage and VRFB stack voltage at the current density of 60  $\text{mA cm}^{-2}$ .

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