Packaging Improvement for Unit Cell Vanadium Redox Flow Battery (V-RFB)

A. C. Khor, M. R. Mohamed, M. H. Sulaiman, M. R. Daud

Abstract—Packaging for vanadium redox flow battery is one of the key elements for successful implementation of flow battery in the electrical energy storage system. Usually the bulky battery size and low energy densities make this technology not available for mobility application. Therefore RFB with improved packaging size and energy capacity are highly desirable. This paper focuses on the study of packaging improvement for unit cell V-RFB to the application on Series Hybrid Electric Vehicle. Two different designs of $25cm^2$ and $100cm^2$ unit cell V-RFB at same current density are used for the sample in this investigation. Further suggestions on packaging improvement are highlighted.

Keywords—Electric vehicle, Redox flow battery, Packaging, Vanadium.

I. INTRODUCTION

ELECTROCHEMICAL with flexibility, scalability and efficiency will be the solution of choice for many applications especially in energy storage system [1], [2]. Advantage of independency power/energy sizing, RFB has high potential in long term development for energy storage system. RFB exhibits similarities with fuel cell characteristics except for having flowing electrolytes which is one of its strength for providing regenerative ability. This technologies employ make use of different type of metal ion couples as reacting species. Examples of this technology included zinc/bromide, iron/chromium, polysulphide/bromide and all vanadium which had been apply from kWh to MWh for peak shaving, frequency regulation, load shifting and power quality control application [2].

Among most flow battery systems, vanadium type RFB commercialized and demonstrated as the most succeeded RFB energy storage by University of New South Wales in the year of 1986. V-RFB technology has captured the eyes of most researchers from all over the world. China, Australia, Russia, United Kingdom, South Africa, Japan and Thailand have explored this technology since past 20 years [3]. The validation of V-RFB in energy storage application especially in renewable energy is shown by Tokuda and his coworkers, they have construct V-RFB stack cell for 450kW application in stationary application [4]. In another major study, Tsuda et al. also fabricated cell stack V-RFB for intermittent PV system [5]. Furthermore, another researcher Li et al. discusses the grouping technology for RFB and promoting the parallel series types scientifically useful as battery energy storage system [6]. V-RFB using same species of metal ion in both electrolytes solves the cross contamination problem face by most RFB enable longer lifespan and will not affect the cell capacity.

The main objective of the present work is to study the improved packaging for V-RFB and to evaluate its benefit against this commercialize technology. In Section II, the related work on V-RFB packaging is provided. The status and trends of traction powers for hybrid electric vehicle are considered in Section II as well. Section III describes the process of experiment detail in our lab. The results are summarized and discussed in Section IV.

II. RELATED WORK

A. V-RFB Description

A V-RFB consists of two external tanks, peristaltic pump and V-RFB cell. The process of Redox happen from time to time when the energy being stored and reduced, electrolyte solution containing redox couples are circulated through the electrodes via reservoirs to the electrochemical compartment. Electrochemical reactions take part in each of the electrode and membrane, often a Nafion® type, is act as the separator to allow transportation of protons toward the current collector thru carbon plate. Reversible electrode reaction take part in reservoir and produce electricity as illustrated in Fig.1.
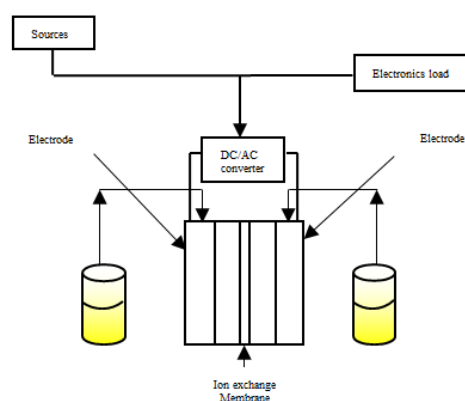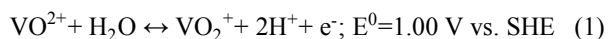

Fig. 1 Simple layout for V-RFB

To date, the homogeneous catalytic reactions proposed are shown as below.

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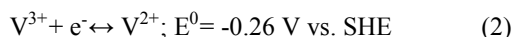
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Positive electrode:

$$VO^{2+} + H_2O \leftrightarrow VO_2^{+} + 2H^+ + e^-; E^0 = 1.00 \text{ V vs. SHE} \quad (1)$$

Negative electrode:

$$V^{3+} + e^- \leftrightarrow V^{2+}; E^0 = -0.26 \text{ V vs. SHE} \quad (2)$$

V^{2+} and V^{3+} indicate the oxidation states of vanadium species.

In order to achieve a better performance, several parameters in V-RFB cell must be optimized. According to Al-Fetawi et al. and coworkers, optimization, scale up and commercialization of V-RFB are dependent on the understanding of several issues, particularly electrolyte stability, carbon oxidation and membrane fouling [7]. However, most of the mechanisms and phenomena regarding packaging improvement are not well understood. There is also limited literature to address the V-RFB packaging design performance and stability significantly.

B. V-RFB Packaging

In the last decade more attention has been focused on the packaging for V-RFB since it has been successfully apply in stationary application such as load leveling, power stabilization for renewable energy and UPS [1], [2], [8]-[10]. Therefore, mobility application for V-RFB also attracted more producers from around the world to explore characterization of compact size with high power rating. According to Mohamed et al. in his paper, he identifies the potential of V-RFB suite as a power source for series hybrid electric vehicle compared to lithium ion and conventional lead acid based on the outstanding performance of V-RFB. Mohamed et al. also commented on the issue of slow charging batteries will be the major obstacle for the HEV market [11]. Together, this study outlines a critical role of packaging improvement in V-RFB.

The characteristics for packaging include the design of cell, electrode design, composition of electrolytes and type of carbon material. Therefore, it has showed the huge possibilities in improving the packaging characteristic to make this technology applicable for mobility usage. In-situ and ex-situ investigation toward the cell indifferent perspective reveal the mechanism detail information and Intel to facilitate the operating condition and electrochemical process for V-RFB. Battery chemistries process that involving reduction and oxidation of metal element require active area on electrode surface for atomistic reaction to take part. Surface active area and composition of porosity carbon felt for Redox process contribute to low potential with high current densities. Heterogeneous and homogeneous species as active reactant for applied electron reaction made the issue of corrosion and contamination to be highlighted in the investigation. Degradation of electrode through corrosion which cause by the strong acidic solution such as H2SO4 decreases performance of battery.

Therefore, electrode design for optimum performance high electronic and ionic conductivity, interfacial electrochemical charge transfer rates, effective mass transfer of the reactant species, low fluid drag and corrosion resistant often discussed in most of the published paper. Bipolar plate electrode and new electrode materials enhance the current densities collective abilities. With the consideration of having suitable composition of electrolyte in V-RFB, Wen et al. pointed out that the optimum concentration of H_2SO_4 is 3mol L^{-1} containing 1.5-2.0mol L^{-1} of V (IV) [12] due to the increasing energy densities and electrode kinetics comprehensively. This conclusion had been made by Wen et al. after apply different concentration of H2SO4 and vanadium solution on the electrode.

Further investigation is made in carbonaceous and non-carbonaceous electrode to find the most suitable electrode material for this technology by most researchers. Referring to his literature, Chakrabatti and coworkers [13] discussed the application of carbon based electrode in his paper to improve the design of carbon based electrode for better RFB performance. The author claims that surface area treatment can improve the reaction kinetics on carbon electrodes.

C. Traction Power for Hev

In this section, review on battery for HEV will be provided. Tie et al. found out 5 types of available battery that suitable for road transportation application which is lead acid, nickel, lithium, zinc air, and ZEBRA battery [14]. However most of the batteries proposed by Tie et al. are energy storage unit without regenerating ability; this cause an extra unit to be installed as the regeneration unit for HEV which is non-cost effective application. There are two types of energy sources needed for HEV which are energy storage and energy generating unit. Most of the electrochemical battery has ability to store energy but cannot generate energy in the same time, unless for fuel cell and redox flow battery. Both types of battery have these abilities which made them favor as energy storage unit.

Fuel cell is more favorable compare to RFB in mobility industries in term of their high energy rating. The similarities of RFB and fuel cell has lured researcher from both field to compare these technologies in term of their effectiveness and efficiency for mobility usage.

With the advantages of decouple capability, modularity, moderate cost and flexibility [1]-[5], [8]-[11], therefore, V-RFB tend to be the promising technology for this newly develop automotive industry [11]. Vanadium holds great promise as supercharger choice in the next decade. This statement was reported by writer Cheryl Kaften in her online article "the next big thing: Vanadium" [15]. The writer believes that vanadium type battery will be on the road along with the electric vehicles within the next decade. EA Technology in Liverpool UK has working on the Ecobus design with VRFB technology, a minibus which travel on a distance of 30km with electrolyte volume 1250L.

III. EXPERIMENTAL DETAIL

Two different sizes and configurations have been modeled and tested in this experiment. Two systems are carried out in

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this test: the first part is based on a 100cm^2 unit cell laboratory V-RFB and the second part is based on a 25cm^2 unit cell laboratory unit V-RFB. Both designs are attached to a combination of reference and working electrodes. The 100 cm^2 unit cell with reference electrodes based system is used at the beginning of the study as it is capable of generalising the V-RFB system. Meanwhile, the second part is done by using 25cm^2 unit cell laboratory units V-RFB is an extension of the initial cell with modification for packaging improvement purpose. Details of both experimental setups have been discussed in paper [11].

The main frame compartments of each reference cell consist of 5cm x 5cm x 2cm polyvinylchloride polymer, separated by an ion exchange membrane. In the center of the half-cell frame, an opening of 1.5cm x 1.5cm is made to allow the vanadium electrolyte flow through and contact between the reference and working electrodes. The reference cell is connected to both V-RFB units. Temperature setting which is 298 ± 2K is maintained throughout the experiment and is monitored using thermocouples in this experiment. Table I expresses the properties of two different unit cells used for this experiment.

TABLE I
SPECIFICATION OF A LABORATORY 100 CM^2 AND 25 CM^2 V^{3+}/V^{4+} RFB [11]

Parameter		
Cell stack body	Polyvinylchloride polymer	
Electrode compartment	100 cm^2	25 cm^2
Cell frame dimension	10 cm x 10 cm x 2cm	5 cm x 5 cm x 2cm
Membrane	Nafion 115/H$^+$	
Porous layer	Carbon felt electrode (Sigratherm GFA5) with effective porosity 0.68 ± 0.07	
Reservoir volume	250 ml	
Vanadium concentration	1.6 mol	
Current	10 A	2.5 A
Volumetric flow rate	100 cm^3 min^{-1} through each compartment	
Temperature	298 + 2 K	

IV. RESULT AND DISCUSSION

TABLE II
NEW CELL VS. OLD CELL COMPARISON

Parameter	25cm^2 unit cell	100cm^2 unit cell
Current density 100mA·cm^{-2}	2.5 A	10 A
Area required for 300 A	3000cm^2 (55 x 55cm)	3000cm^2 (55 x 55cm)
V$_{Dischargeave}$	1.20 V	1.10 V
Cell$_{Required}$	60 + 2cm frame = 62cm	60 + 4cm frame = 70cm
Cell stack volume	155 L	212 L
For 25 Wh L^{-1}	317 L	317 L
Total	472 L (379 kg*)	529 L (424kg)

*1.6 M V (III)/V (IV) + 4 M H$_2$SO$_4$ =1.246 kg·L

In this study, University of Southampton series hybrid vehicle with extended range of 300km has been used. Table II presents the results obtained from the experiment. The results of this study will now be compared to the findings of previous work [11]. As shown in Table II, 25cm^2 unit cell shows the significant reduction on the cell stack volume to produce the

similar energy rating as 100 cm^2 unit cell. For specification of 72 V battery capacity 110 ampere-hour and 300 A, lithium ion battery weight 60 kg and 96 L. Lead acid weight 250 kg and 300 L. As the relationship of area is direct proportional with current, 3000 cm^2 which approximately 55 cm x 55 cm is needed for 300 A current densities. For V-RFB, each cell have a potential of 1.10 V, therefore we need 66 units cell in stack for 72 V. The thickness per cell is 1 cm; the total length for this stack will be approximately 68 cm. Total volume for V-RFB cell stack is 212 L.

By using Faraday's Law of electrolysis:

$$q = \frac{zFV\Delta c}{M} \qquad (3)$$

where q is the total stored charge, z is the number of electrons transferred during the redox reaction which is 1 for V-RFB. F is Faraday constant (26.8 A h mol^{-1}), V is the volume of the reactants, Δc is the reactant concentration (approximately 1.6 mol L^{-1} for the test cell) and M is the molar mass of the reactant (50.94g mol^{-1} for vanadium).

Theoretically, the required volume of reactants is 30Wh L^{-1}. Assuming low practical energy density of 25 Wh L^{-1}, V$_{Electrolyte\ required\ (72\ V,\ 110Ah,\ 300A)}$ = 317L. The total volume and mass of the V-RFB needed for the case study vehicle are 529 liters and 424kg respectively. This is much larger than the lithium-ion battery and 50% larger in volume than the conventional lead-acid.

V. CONCLUSION

The initial design of this cell was used to perform a better energy yield with smaller size which in the future would be prospect for cost effectiveness. This study set out to determine the size effectiveness for V-RFB is non-directly proportional with the energy rating. It is recommended that further research be undertaken in the following areas: nanotube carbon polymer, membrane, stacks cell development and also material study for felt.

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