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Numerical study on vanadium redox flow battery performance with non-uniformly compressed electrode and serpentine flow field

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HIGHLIGHTS

- A non-uniform model of VRFB electrode compression with flow field is proposed.
- Non-uniform electrode deformation and physical properties are fully considered.
- Intrusion ratio, local porosities and permeabilities under compression are measured.
- Velocity profile, local current density, and overpotential fluctuation are obtained.
- Appropriate compression of 55.7% can exhibit maximum comprehensive performance.

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ABSTRACT

Electrode compression is an effective approach to enhance the performance of vanadium redox flow battery (VRFB). Electrode compression can decrease the contact resistance between the electrode and the current collector. Porous electrode compression and deformation are not uniform because of the rib-channel patterns and part of the fibers pressed into the channel. The effects of the non-uniform deformation of a compressed electrode on the performance of a VRFB with flow field are not fully analyzed. In this study, a non-uniform model is proposed to consider the electrode shape deformation and non-uniformity of physical properties inside a compressed electrode. Morphological features of a deformed electrode including the intrusion ratio and local porosities under compression are investigated. Non-uniformly compressed electrodes with different local porosity and permeability are obtained. The predicted cell performance is initially validated using experiment data. The performance of VRFB with non-uniformly compressed electrode and serpentine flow field are investigated under different compression ratios (CRs). The non-uniform model can reasonably predict the charge/discharge and flow behavior. The velocity profile, local current density, and overpotential fluctuation along the rib and channel regions are obtained. The bulk velocity associated with species transport is improved because of the decreased cross-section areas of the flow channel inside the compressed electrode. An appropriate compression can improve the VRFB performance because of the enhanced species transport and increased reaction area when the intrusion part is considered. An optimized electrode CR of 55.7% is found to exhibit the maximum concentration uniformity as well as the minimum current density and overpotential. The present model can guide the VRFB design when the compressed electrode is considered.

1. Introduction

The vanadium redox flow battery (VRFB) shows some unique characteristics such as the flexible energy design, power ratings, and long life cycle [1]. Thus, the VRFB becomes a prospective energy storage technology for a distributed power generation system [2,3] and for stabilizing the local grid electricity supplies [4]. The VRFB is an electrochemical system which stores energy in the circulating vanadium-based electrolyte. A typical VRFB cell consists of a cathode, an anode, and a hydrogen ion exchange membrane separator. The separator permits diffusion of hydrogen ion to maintain the electroneutrality and electrolyte balance and prevent two electrolyte solutions from cross-mixing [5]. The VRFB solutions consisting of V^{2+}/V^{3+} and VO^{2+}/VO_2^+ are pumped continuously from the external tanks.

Extensive studies have been conducted to optimize the structure design and the control strategy of VRFB [6]. In the experimental study, the local distributions of species concentrations and current density cannot be estimated. Due to the limitations of the experimental

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Nomenclature

CR	compression ratio
Re	Reynolds number
C	concentration
V	volume
A	area
Q	volumetric flow rate
ΔP	pressure drop
T	temperature
E	potential
P	pressure
D	diffusivity
F	Faraday constant
N	specie flux
R	gas constant
J	current density
SOC	state of charge
K	permeability
W	width
L	length
ω	volumetric flow rate
k	reaction rate
ν	electrolyte kinematic viscosity
ρ	electrolyte density
z	stoichiometric number
d_f	fiber diameter
δ	conductivity
u	velocity vector
h	thickness
ε	electrode porosity
i	applied current density
η	overpotential
α	transfer coefficients

Superscripts

s	surface
*	normalized value
eff	effective
0	equilibrium state
u	volume average uniformity factor

Subscripts

i	species chosen
s	solid phase
l	liquid phase
0	initial state
a	anodic
c	cathodic
1	positive
2	negative
loc	local
p	bulk porous electrode
ip	intrusion porous electrode
ave	average
in	inflow
out	outflow
pe	penetration
m	membrane
ch	channel
la	land

technique, numerical methods with different types of models are widely used for the VRFB performance prediction. Presently, the VRFB models include the mesoscopic model [7,8], the macroscopic multi-physics model [9,10], and the control-oriented model [11–13]. Mass transport enhancement is one of the critical methods to improve the VRFB performance. In the commonly used flow-through battery architecture (without flow field), an electrolyte is directly injected into the electrode from one lateral side. As the active reactants are consumed along with the electrolyte flow, the in-plane non-uniform ion concentration distribution exists within the flow-through pattern which leads to the deterioration of mass transport in the region far from the inlet. Based on the numerical study of Al-Fetlawi at al. [14], a significant non-uniformity in the reactant concentration distribution was observed in the VRFB with no flow field especially at high stages of discharge (SOC) or current densities. Tang et al. [15] pointed out that the increasing flow rate can improve the concentration distribution uniformity within the flow-through pattern. However, this approach leads to a large parasitic pumping loss which decreases the system efficiency. To deal with this issue, a flow field is introduced into the battery structure and placed between the current collector and the porous electrode. A reasonable flow field design could improve the mass transport with a low parasitic pumping loss. In the VRFB designed with flow field, electrolytes firstly flow into the flow channel and transport inside the conterminous porous electrode by convection and diffusion. Xu et al. [16,17] compared the performances of VRFB with the serpentine flow field and without flow field, and found that the former can improve the distribution uniformity of electrolyte and reduce the overpotential in the electrode. The VRFB with serpentine flow fields exhibits a 5% higher efficiency than that without flow fields at their corresponding optimum flow rate. The inclusion of a flow field can effectively manage the reactant concentration distribution in both in-plane and through-plan directions inside the electrode. Moreover, the optimization designs of the flow field structure for VRFB are discussed and used to achieve more uniform reactant concentration distribution with lower pumping power. Zhu et al. [18] designed a forced convection flow pattern, in which the porous electrode between two parallel flow field plates were inserted, and the effects of the arrangement of the two parallel flow field plates was discussed. They found that the energy efficiency of the VRFB with two parallel flow field plates in staggered arrangement is increased by 5% compared with that in symmetrical arrangement. This enhancement is mainly caused by the increased area, effective utilization, and improved uniformity of concentration distribution. Yin et al. [19] designed the single flow inlet and multi-inlet patterns, and they found that the multi-inlet design presents efficiency of electrode utilization at relativity high electrolyte flow rates. The VRFB with flow fields generally exhibit an improved performance, especially at high flow rates because of the convective mass transfer enhancement of reactant.

In addition, some visible challenges such as low ion transport of active species in electrolyte and sluggish electrochemical kinetics of electrode still prevent VRFBs from widespread commercialization. The electrode not only provides activity sites for electrochemical reactions but also offers a flow path for species transport and electron transfer. The porous carbon or graphite felts with high porosity commonly serve as the electrode in VRFBs. Carbon and graphite felts are preferable electrode materials because of their three-dimensional network structure, high specific surface area, and high electrochemical stability. However, electrode materials should still be modified to improve the reversibility and electrocatalytic activity of the electrode [11]. Sun and Skyllas-Kazacos [20,21] investigated the effects of thermal and acid treatments on carbon and graphite felts. The increased chemisorbed oxygen, dropped cell resistance, and improved energy efficiency are