International Communications in Heat and Mass Transfer 75 (2016) 7–12

Contents lists available at ScienceDirect

International Communications in Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ichmt

Scale-up of high power density redox flow batteries by introducing interdigitated flow fields☆

Xin You, Qiang Ye *, Ping Cheng

Ministry of Education Key Laboratory of Power Machinery and Engineering, School of Mechanical Engineering, Shanghai Jiao Tong University, Shanghai 200240, PR China

ARTICLE INFO

Available online 11 April 2016

Keywords:
Flow battery
Thin electrode
Large scale
Flow fields

ABSTRACT

Lab-scale redox flow batteries (RFBs) employing thinner electrodes have achieved outstandingly high power densities. When these high-performance thinner electrodes are scaled up to larger sizes required for kW-scale stacks, adding interdigitated flow fields is a simple solution in maintaining low pressure drops. A 3-D model of a half-battery with an active area of 900 cm^2 was developed to explore the design rules of flow fields. Optimizing the number and size of channels is essentially striking a balance between the pressure drop and the electrolyte velocity in the electrode, which have important effects on the pumping loss and mass transport loss respectively. In addition to the magnitude of the average velocity, the uniformity of velocity distribution should also be paid attention to in designing flow fields, which is determined by the ratio of flow resistance in the electrode to that in the channels. Acceptably thicker channels are recommended to improve uniformity of velocity distribution.

1. Introduction

Redox flow batteries have been regarded as a promising candidate for the large-scale electrical energy storage (EES) [1–4]. In contrast to conventional secondary batteries, power and energy capacity of RFBs can be designed separately. Among numerous existing kinds of RFBs, the all-vanadium redox flow battery (VRFB), utilizing just a single element with four different oxidation states as reactants, has received most attention owing to its freedom from cross-contamination. In most of conventional VRFB designs, graphite felts are utilized as electrodes owing to the sufficient chemical stability and low cost. Recently, a number of publications about VRFB focus on improving the power density of lab-scale single cell by exploring alternative electrode materials. Aaron et al. [5] fabricated a 5 cm^2 VRFB by using carbon papers as electrodes and obtained a peak power density of 557 mW cm^{-2}, the highest performance reported by that time. Before long, the peak power density was further increased to 767 mW cm^{-2} in the same group [6] by using thermally pretreated carbon papers and a thinner membrane. By far, the highest power density of a lab-scale single VRFB (1350 mW cm^{-2}) was obtained by using thin electrodes in the UTRC Inc. [7]. Accordingly, compared with conventional graphite felt, the cell with thinner and denser carbon paper is more capable of achieving high power density, which is attributed to larger specific surface area and smaller ohmic resistance (both electronic and ionic). However, when these high power density RFBs are scaled up, high feeding rates of the electrolyte through these thinner and denser electrodes lead to unacceptably high pressure drops if conventional flow through mode is adopted.

To avoid excessive pumping loss, introducing flow fields in either the bipolar plates or the porous electrodes is essential when the electrodes become larger and thinner. There are a large variety of flow fields being put forward for fuel cells originally [8,9], among which the serpentine flow field (SFF) and interdigitated flow field (IFF) are the two most widely adopted flow fields in RFBs [5,6,10–13]. The design with SFF adjacent to porous electrode is generally considered as a typical flow-by configuration, where the transport of reactant from channels to the electrode is dominated by diffusion if the effect of under-rib convection is negligible [14]. Unlike gas reactant in fuel cells, reactant species in the liquid electrolyte have much lower diffusivities, leading to the fact that the reactant transport depends primarily on convection. Xu et al. [10,11] found that the benefit of adding SFF to lab-scale VRFB performance only appears at high flow rates, which enhance the under-rib convection at the expense of increased pumping power. A RFB design adopting IFF is intrinsically flow-through configuration. Due to the disconnection between inlet and outlet channels, the electrolyte is forced to flow through the electrode under the land. Benefiting from enhanced convection in electrode, the cell with IFF generally presents better electrochemical performance than the cell with SFF, especially at high current densities [12,13]. Compared with the complete flow-through configuration, adding IFF effectively reduces the pressure drop by shortening the flow length and undesirably decreasing the electrolyte velocity in electrode, which is a critical parameter for mass transport. If the velocity is excessively decreased by adding superabundant channels, significant mass transport resistance might lead to a poor electrochemical performance [15]. Therefore, there exists a trade-off between the pressure drop and the velocity in designing IFF. The fluid

☆ Communicated by Dr. W.J. Minkowycz.

* Corresponding author.
E-mail address: qye@sjtu.edu.cn (Q. Ye).

http://dx.doi.org/10.1016/j.icheatmasstransfer.2016.03.021
0735-1933/

Nomenclature

I	identity matrix
p	pressure (Pa)
U	uniformity factor
u	velocity ($m\ s^{-1}$)
V	volume (m^3)

Greek letters

ε	porosity
κ	permeability (m^2)
μ	dynamic viscosity (Pa s)
ρ	density ($kg\ m^{-3}$)

Subscript

m	mean value

dynamic characteristics of adding flow fields adjacent to the porous electrode are essential to understand the fundamentals in optimizing the flow field design. Although several hydrodynamic analyses have been reported for lab-scale RFBs [16–18], systematical investigations for utility-scale RFBs are scarce, which is the major motivation of this study.

In this work, a 3-D model is developed to explore the design rules of flow fields for utility-scale RFBs. The number and size of interdigitated flow channels are adjusted to probe the trade-off between pressure drop and electrolyte velocity. Special attentions are paid to the uniformity of velocity distribution. The rest of this paper is organized as follow. The assumptions, governing equations and boundary conditions of this model are described in Section 2. Section 3 presents and discusses effects of key designing parameters on pressure drop, magnitude and distribution of electrolyte velocity, which is followed by major conclusions and suggestions in Section 4.

2. Model description

Considering the symmetric geometry-structure of each single cell, it is adequate to investigate the flow features in a half-cell. The simulated domain consists of a porous electrode and interdigitated flow channels as shown in Fig. 1. A group of inlet/outlet channels comprise a main channel and several branching channels. The number of outlet branching channels is always one less than that of inlet branching channels. To prevent the short cut of electrolyte flow, the main inlet channel and main outlet channel are both placed away from the electrode.

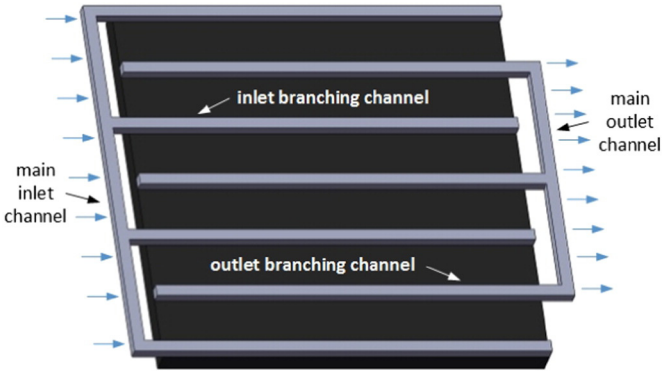

Fig. 1. Example of an electrode divided into 6 segments by introducing 4 inlet branching channels and 3 outlet branching channels.

2.1. Model simplifications and assumptions

Several simplifications and assumptions of the present model are as follows: 1) the electrolyte flow is regarded as incompressible flow; 2) the volume change of the electrolyte caused by water crossover is neglected; 3) the electrode properties are isotropic and the intrusion of electrode in the channel volume is not considered; 4) the temperature is invariant.

2.2. Governing equations and boundary conditions

According to the incompressible assumption and negligible volume change of electrolyte, the continuity equation of electrolyte applicable to the entire domain is given as follow:

$$\nabla\cdot\vec{u} = 0. \tag{1}$$

Navier–Stokes equations and Brinkmann equation are the momentum equations in flow channels and the porous electrode respectively:

$$\rho\left[\left(\vec{u}\cdot\nabla\right)\vec{u}\right] = \nabla\cdot\left[-p\mathbf{I} + \mu\left(\nabla\vec{u} + \left(\nabla\vec{u}\right)^T\right)\right] \tag{2}$$

$$\frac{\rho}{\varepsilon}\left[\left(\vec{u}\cdot\nabla\right)\frac{\vec{u}}{\varepsilon}\right] = \nabla\cdot\left[-p\mathbf{I} + \mu\left(\nabla\vec{u} + \left(\nabla\vec{u}\right)^T\right)\right] - \frac{\mu}{\kappa}\vec{u} \tag{3}$$

where ρ is the electrolyte density, p is the pressure, **I** is the identity matrix, μ is the electrolyte viscosity, ε represents the electrode porosity and κ denotes the electrode permeability. Values of these parameters are listed in Table 1.

By setting continuous velocities and pressures across the interface between channels and the porous electrode, flow parameters are coupled in the whole domain. Based on the research in optimizing the uniformity of inlet velocity [19], it is reasonable to give evenly distributed velocities as the inlet boundary condition along the entrance of the main inlet channel. Inlet velocities are obtained by dividing the volumetric flow rate by the entrance area. At the exit of the main outlet channel, the pressure is set constant. The velocity is set as zero on the walls of flow channels.

2.3. Numerical method

The continuity and momentum equations listed above are solved numerically by using finite element software COMSOL Multiphysics®. The total grid number ranges from 15,330 to 94,520 for different configurations, and the relative tolerance is set as 1×10^{-6}.

3. Results and discussions

Under typical operational conditions, the pressure drop of electrolyte flow across the electrode without flow field is calculated firstly to

Table 1
Fundamental parameters.

Symbol	Description	Value
H_e	Electrode thickness (mm)	1[a]
L_e	Electrode length (cm)	30
W_e	Electrode width (cm)	30
ε	Electrode porosity	0.88[b]
κ	Electrode permeability (m^2)	3×10^{-11} [20]
ρ	Density of electrolyte ($g\ cm^{-3}$)	1.354 [21]
μ	Dynamic viscosity of electrolyte (mPa s)	5 [21]
ω	Volumetric flow rate ($L\ min^{-1}$)	1.68
p_{out}	Pressure at outlet (atm)	1

[a] Approximated based on references [5,6].
[b] Estimated.