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A simple analytical model of coupled single flow channel over porous electrode in vanadium redox flow battery with serpentine flow channel☆

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HIGHLIGHTS

- An analytical model for vanadium RFBs with serpentine flow channel is developed.
- The flow velocity distributions in the porous electrode is analyzed.
- Effects of geometry parameters on flow rate penetrating in electrode are studied.
- The maximum current density achieved based on reactant flow rate is predicted.

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ABSTRACT

A simple analytical model of a layered system comprised of a single passage of a serpentine flow channel and a parallel underlying porous electrode (or porous layer) is proposed. This analytical model is derived from Navier–Stokes motion in the flow channel and Darcy–Brinkman model in the porous layer. The continuities of flow velocity and normal stress are applied at the interface between the flow channel and the porous layer. The effects of the inlet volumetric flow rate, thickness of the flow channel and thickness of a typical carbon fiber paper porous layer on the volumetric flow rate within this porous layer are studied. The maximum current density based on the electrolyte volumetric flow rate is predicted, and found to be consistent with reported numerical simulation. It is found that, for a mean inlet flow velocity of 33.3 cm s^{-1}, the analytical maximum current density is estimated to be 377 mA cm^{-2}, which compares favorably with experimental result reported by others of ~400 mA cm^{-2}.

1. Introduction

Studies on redox flow batteries (RFBs) with flow fields (such as serpentine flow channels and interdigitated flow channels) that evolved from PEM fuel cell designs have gained more attention. The thin carbon fiber paper electrodes used in the RFBs with flow fields give much lower ohmic losses compared with the conventional flow batteries with thicker carbon felt electrodes. A much higher current density can be achieved in the RFBs with the thin carbon fiber electrodes.

Results reported by Zawodzinski and Mench et al. [1] of the "zero-gap" flow battery prototype design utilizing an architecture of the serpentine flow channel flow field demonstrate performance at a higher current density and power density in contrast to flow batteries without flow fields. Xu et al. [2] compared cell performance of the vanadium RFBs between without and with flow fields. Higher round trip efficiency is found in the latter. Latha et al. [3] studied the flow dynamics, including flow velocities and pressure drops in the all-vanadium RFBs with the serpentine flow channel. Ke et al.'s [4,5] macroscopic mathematical model of mass transport

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in RFBs with a single passage of the serpentine flow channel shows flow distributions in the porous electrode, flow reactants consumption within the porous layer and predicts a maximum current density in agreement with experimental data reported in the literature. Brian et al. [6] developed an organic Quinone-Bromine flow battery with interdigitated flow channels, and high power density has been observed in this type of flow cell. Mayrhuber et al. [7] used a laser perforation approach to generate holes among the structures of the carbon fiber paper electrodes in the RFBs with the serpentine flow channel. It has been found that those holes can help to enhance electrolyte flow and consequently mass transfer and penetration in the porous electrode and a higher power density can be achieved. Nevertheless, excessive holes can result in smaller active surface area, which leads to a degradation of the performance.

In this work, a simple analytical model is presented to help understand high performance achieved in the vanadium flow battery with the serpentine flow channel. The model can be applied to any flow battery half-cell that has a true redox reaction with all species soluble in the electrolyte and where a serpentine flow field is used for enhanced power density. These include the all vanadium and iron-vanadium systems, the iron-chrome systems and the positive half-cells of the all iron and metal-halogen systems.

2. Zero-gap flow cell construction

This “zero-gap” flow cell architecture shown as Fig. 1 has been first reported by Zawodzinski and Mench et al. [1] in the flow batteries with thin carbon fiber paper electrode, which gives a much smaller ohmic's loss while enabling higher limiting current density. This flow cell is modified from the fuel cell configuration of a direct methanol fuel cell (DMFC) or a proton exchange membrane fuel cell (PEMFC) design.

3. 2D Flow structure

The 2D (X, Y) diagram of the electrolyte flowing through a single passage of the serpentine flow channel and over the porous electrode is described in Fig. 2. The parameters t_f, t_p and L are the thickness of the flow channel, thickness of the porous layer and length of the flow channel/porous layer, respectively. Three boundaries are denoted by BC#1 (interface boundary between the current collector and the flow channel), BC#2 (interface boundary between the flow channel and the porous layer) and BC#3 (interface boundary between the porous layer and the ion selective membrane).

4. Analytical model

This macroscopic model for the flow motions in the single passage of the serpentine flow channel and the porous layer was proposed and examined numerically by Ke et al. [4,5]. The assumptions of the fluid flow model include incompressible and Newtonian fluid, steady state and laminar flow with no gravity effect. The results reported in Ref. [4] illustrates the flow physics in the flow channel and the porous layer along both the X and Y directions. Further details of deriving the motion equations can be found in the ref. [5]. The flow patterns evolving from an entrance profile to developing, developed and fully developed regime in the flow channel and the porous layer under the ideal plug flow and parabolic flow inlet boundary conditions were studied.

In this contribution, a simple analytical solution of the model proposed and numerically analyzed by Ke et al. [4,5] is presented. As fully developed region in the porous layer is approached, the velocities in the Y direction approach to be zero. Under this condition, the total volumetric flow rate transferred from the flow channel into the porous layer is estimated. The flow motion along the X direction in the porous layer can be written as

$$\varepsilon\nabla\left\langle p_p\right\rangle = \mu\nabla^2\left\langle u_p\right\rangle - \frac{\mu\varepsilon}{k}\left\langle u_p\right\rangle \tag{1}$$

In the flow channel, the Navier–Stokes motion is simplified as

$$0 = -\nabla p_f + \mu\nabla^2 u_f \tag{2}$$

In the fully developed region, the pressure gradient along the flow channel and the porous layer is equal. The boundary conditions are defined as follows.

(a) BC#1-upper wall of the flow channel: $0 \le X \le L$, $Y = t_f$, $u_f = 0$;
(b) BC#2-interface between the flow channel and the porous layer: $0 \le X \le L$, $Y = 0$, $u_f = \langle u_p\rangle$; $\partial u_f/\partial Y = \varepsilon^{-1}\partial\langle u_p\rangle/\partial Y$ (continuities of flow velocity and normal stress at the interface) [5];
(c) BC#3-bottom wall of the porous layer: $0 \le X \le L$, $Y = -t_p$, $\langle u_p\rangle = 0$.

As the fully developed region is approached, the conservation of volumetric flow rate gives

$$Q_{in} = \left(Q_f\right)_{fd} + \left(Q_p\right)_{fd} \tag{3}$$

Where, the total of volumetric flow rate Q_{in} is equal to the volumetric flow rates in the channel plus the porous layer, $(Q_f)_{fd} + (Q_p)_{fd}$. Where, Q_{in}, $(Q_f)_{fd}$ and $(Q_p)_{fd}$ are denoted as follows

$$Q_{in} = u_{in} t_f w_f \tag{4}$$

$$\left(Q_f\right)_{fd} = w_f \int_0^{t_f} \left(u_f\right)_{fd} dY \tag{5}$$

$$\left(Q_p\right)_{fd} = w_p \int_{-t_p}^{0} \left(u_p\right)_{fd} dY \tag{6}$$

Here, w_f is equal to w_p. Through applying the conditions of BC#1, BC#2, BC#3 and conservation of volumetric flow rate, the analytical solutions for velocities and volumetric flow rates in the fully developed region of the flow channel and the porous layer are obtained, respectively

$$\left(u_f\right)_{fd} = 0.5\frac{C_0}{\mu}Y^2 + C_1 Y + C_2 \tag{7}$$

$$\left(\left\langle u_p\right\rangle\right)_{fd} = C_3 e^{\sqrt{\frac{\varepsilon}{k}}Y} + C_4 e^{-\sqrt{\frac{\varepsilon}{k}}Y} + C_5 \tag{8}$$

The corresponding equations of volumetric flow rate in the flow channel and the porous layer are shown below

$$\left(Q_f\right)_{fd} = \frac{1}{6}\frac{C_0}{\mu}t_f^3 w_f + 0.5 C_1 t_f w_f + C_2 t_f w_f \tag{9}$$

$$\left(Q_p\right)_{fd} = \sqrt{\frac{k}{\varepsilon}} w_p \left(C_3\left(1 - e^{-\sqrt{\frac{\varepsilon}{k}}t_p}\right) - C_4\left(1 - e^{\sqrt{\frac{\varepsilon}{k}}t_p}\right)\right) + C_5 t_p w_p \tag{10}$$

Here,