Journal of Power Sources 299 (2015) 509–518

Contents lists available at ScienceDirect

Journal of Power Sources

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

Distribution of incompressible flow within interdigitated channels and porous electrodes

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HIGHLIGHTS

- Modeled interdigitated channel flow connected by porous electrodes.
- Generalized results in terms of dimensionless groups.
- Quantitative design guidelines for optimizing channel layouts for flow batteries.
- Reported graphical and analytic representations of design guidelines.

ARTICLE INFO

Article history:
Received 13 August 2015
Received in revised form
2 September 2015
Accepted 3 September 2015
Available online xxx

Keywords:
Interdigitated channels
Flow battery
Fuel cell
Porous media
Design guidelines

ABSTRACT

This paper develops a general model with which to evaluate flow uniformity and pressure drop within interdigitated-channel structures, especially in the context of redox flow batteries. The governing equations are cast in dimensionless variables, leading to a set of characteristic dimensionless parameter groups. The systems of governing equations are solved computationally, with the results presented graphically. Because the results are general, the underlying model itself is not needed to apply the quantitative design guidelines. However, the paper presents and discusses all the information required to recreate the model as needed.

1. Introduction

Redox flow batteries, polymer-electrolyte fuel cells (PEMFC), and potentially other technologies can be designed with interdigitated channels that supply flow through underlying porous electrode structures. Device performance often depends on tradeoffs between flow uniformity over large areas and overall pressure losses.

The objective of the present paper is to develop quantitative guidelines that assist the design of interdigitated-channel configurations and operating conditions. The approach is based upon a combination of models that are formulated in terms of characteristic dimensionless groups. The results are presented graphically, revealing quantitative tradeoffs between flow uniformity and pressure drop. The model results are reduced to a general set of design guidelines that do not require running the model for particular geometric configurations or operating conditions.

Fig. 1 illustrates some of the salient features of an interdigitated redox flow battery layout. Small rectangular flow channels are situated within the bipolar plates. The “feed” channels are completely closed at the exit end of the structure, and “exhaust” channels are completely closed at the entrance end of the structure. Thus, all the fluid (electrolyte) that enters the feed channels must flow through the porous electrodes and leave via the exhaust channels. Electrochemical reactions proceed within the porous electrodes, with ion mobility across the membrane that separates the anode and cathode.

A variety of channel layouts, including interdigitated channels, are used in redox flow batteries [1–5] and fuel cells [6–16]. Much of the modeling literature is based on various approaches for two- and three-dimensional computational fluid dynamics. Some investigations specifically consider under-rib convection, especially for PEMFC serpentine designs [17–19]. Most models also

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http://dx.doi.org/10.1016/j.jpowsour.2015.09.013
0378-7753/

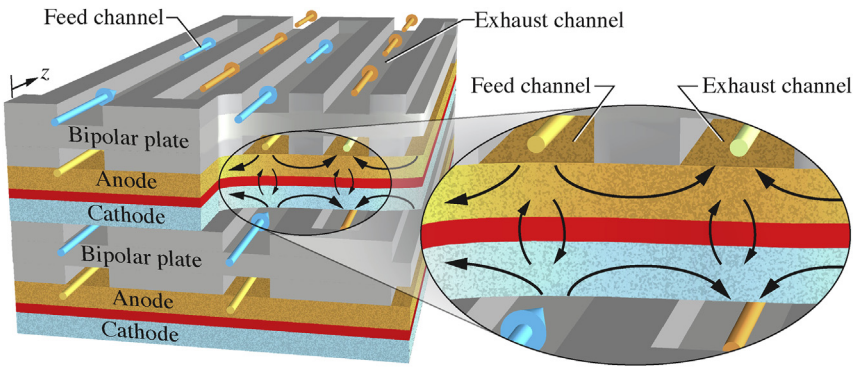

Fig. 1. Illustration of a segment of redox flow battery with interdigitated channels in the bipolar plates. The anode and cathode structures are separated by ion-transport membranes.

incorporate electrochemistry as well as ion mobility across the membrane that separates anode and cathode. In essentially all cases, the physical problem is solved directly, without an attempt to generalize in dimensionless terms.

The present paper is devoted entirely to flow distribution; it does not consider chemistry or electrochemistry within the porous structures. Flow batteries are often designed with relatively low single-pass conversion within the porous electrode structures. Thus, it is reasonable to neglect the effects of electrode chemistry and membrane transport when considering the flow distribution. The important contribution of the present approach is to develop generalized, but quantitative, guidelines for the flow distribution.

Although the results of the present analysis are general, there are also limitations based upon physical assumptions. The model is certainly compromised if the mass transport across the ion-transport membrane (cf., Fig. 1), is comparable to the mass transport between channels. The model assumes fully developed flow within the channels (i.e., entry-length effects are neglected). Laminar flow is typical in flow-battery channels, but the model is not restricted to laminar flow. For gas-phase flows (e.g., as in PEMFC), the incompressibility assumption can be compromised. Although including an equation of state in the model itself is easily done, doing so limits the generality of the dimensionless results. Finally, molecular diffusion is neglected. In applications such as PEMFC fuel cells with gaseous fuels, axial diffusive transport within the channels and molecular diffusion within the gas-diffusion structures can play important roles.

The model focuses specifically on two interdigitated channels and the underlying porous structure. Thus, there is an implicit assumption that each channel pair within a full battery layout behaves the same as all others. In other words, the manifold or header structures are designed to feed all the interdigitated channels equally.

The theoretical and computational approach developed here has its foundation in earlier models for flow distribution in parallel-flow header-channel configurations [20]. The new elements of the present paper are related to the generalization of flow through porous electrode structures that connect the interdigitated channels. The present model and the dimensionless results provide easy-to-use design guidance. Nevertheless, it is also clear that complete design process benefits greatly from much more detailed models that incorporate chemical, electrochemical, and thermal behaviors.

2. Channel flow

Assuming steady-state, single-component, isothermal, incompressible, plug flow, the mass-continuity equations within the channels can be written as

$$\rho \frac{\mathrm{d}u_\mathrm{f}}{\mathrm{d}z} = -\frac{K\left(p_\mathrm{f} - p_\mathrm{e}\right)}{H_\mathrm{c}}, \tag{1}$$

$$\rho \frac{\mathrm{d}u_\mathrm{e}}{\mathrm{d}z} = +\frac{K\left(p_\mathrm{f} - p_\mathrm{e}\right)}{H_\mathrm{c}}, \tag{2}$$

where u_f and u_e are mean velocities in the feed and exhaust channels, respectively. The rectangular channels are assumed to be W_c wide, H_c high, and L_c long. The independent variable z is the axial position within the channels. The mass flux between adjacent channels (i.e., through the underlying porous media) can be represented as

$$m'' = K\left(p_\mathrm{f} - p_\mathrm{e}\right), \tag{3}$$

where p_f and p_e are the local pressures within the feed and exhaust channels, respectively. The "flux" is referenced to the surface area on the floor of the channels. The parameter K is a function of the porous-media properties and physical dimensions, but is assumed to be a constant for any particular system.

The axial momentum equations within the channels can be written as

$$\frac{\mathrm{d}\left(\rho u_\mathrm{f} u_\mathrm{f}\right)}{\mathrm{d}z} = -\frac{\mathrm{d}p_\mathrm{f}}{\mathrm{d}z} - \tau_\mathrm{w}\frac{P_\mathrm{c}}{A_\mathrm{c}}, \tag{4}$$

$$\frac{\mathrm{d}(\rho u_\mathrm{e} u_\mathrm{e})}{\mathrm{d}z} = -\frac{\mathrm{d}p_\mathrm{e}}{\mathrm{d}z} - \tau_\mathrm{w}\frac{P_\mathrm{c}}{A_\mathrm{c}}, \tag{5}$$

where τ_w is the local shear stress at the channel walls, $P_\mathrm{c} = 2(W_\mathrm{c} + H_\mathrm{c})$ is the channel's wetted perimeter, and $A_\mathrm{c} = W_\mathrm{c}H_\mathrm{c}$ is the channel's cross-sectional area. Because the mass flux between the channels is assumed to be normal to the axial direction, a mass-flux term does not directly appear in the axial momentum equations. However, the mass flux is indirectly involved via the velocity coupling with the continuity equations.

The wall shear stress can be represented in terms of a friction factor as

$$f = \frac{\tau_\mathrm{w}}{\rho u^2/2}. \tag{6}$$

For fully developed laminar flow in a rectangular channel, the