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Review

Effective transport properties for polymer electrolyte membrane fuel cells – With a focus on the gas diffusion layer

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ABSTRACT

Multi-phase transport of reactant and product species, momentum, heat (energy), electron and proton in the components of polymer electrolyte membrane (PEM) fuel cells forms the three inter-related circuits for mass, heat (energy) and electricity. These intertwined transport phenomena govern the operation and design, hence the performance, of such cells. The transport processes in the cell are usually determined with their respective effective transport properties due to the porous nature of PEM fuel cell components. These properties include the effective diffusion coefficient for the mass transfer, effective thermal conductivity for heat transfer, effective electronic conductivity for electron transfer, effective protonic conductivity for proton transfer, intrinsic and relative permeability for fluid flow, capillary pressure for liquid water transfer, etc. Accurate determination of these effective transport properties is essential for the operation and design of PEM fuel cells, especially at high current density operation. Thus, it is the focus of intensive research in the recent years. In this article, a review is provided for the determination of these effective transport properties through the various PEM fuel cell components, including the gas diffusion layer, microporous layer, catalyst layer and the electrolyte membrane layer. Given the simplicity of the GDL in structure compared to the other components of the cell, much more work in literature is focused on its transport properties. Hence, its review in this paper is more extensive. Various methods used for the determination of the effective transport properties with and without the presence of liquid water are reviewed, including experimental measurements, numerical modeling and theoretical analyses. Correlations are summarized for these transport properties, where available and further work in this area is provided as a direction for future work.

Contents

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1. Introduction

Global population increase and social-economic development have escalated energy demands, and harmful chemical and greenhouse gas emissions accompanying the excessive energy requirement met through the use of fossil fuels degrade local and global environment and pose health hazards to earth inhabitants. The dominance of a single energy resource also shakes the security of access to and distribution of energy. Diversity in energy sources is crucial in meeting today's energy demands, ensuring energy security and minimizing the impact on the environment [1,2]. With its high energy efficiency and minimal total emissions, polymer electrolyte membrane (PEM) fuel cell is considered a major player in energy diversification. It has a wide spectrum of practical applications ranging from mobile (transportation), to stationary co-generation, and to portable consumer electronics.

PEM fuel cell is an electrochemical device, which converts the chemical energy of hydrogen and oxygen efficiently into electrical energy, as schematically shown in Fig. 1 [3]. A PEM fuel cell is composed of an anode electrode, where hydrogen is supplied as the fuel and a cathode electrode, where oxygen or air is supplied as the oxidant. The porous anode and cathode electrode are made of a gas diffusion layer (GDL), a catalyst layer (CL), and often a microporous layer in between the GDL and CL to facilitate water transport and removal, an issue especially important for the cathode side. The catalyst layer consists of electrochemical catalyst particles (often platinum) supported on larger carbon particles, ionomer that surrounds the supported catalyst particles and void space. During operation, hydrogen gas through the flow channels built on the anode flow distribution (also often called bipolar) plate is supplied to the anode, its major flow direction is parallel to the anode electrode surface. Through the combined effect of convection and diffusion, although diffusion is considered to play a significant, even dominant role, hydrogen is transported through the anode GDL to the anode catalyst layer (ACL), dissolved into the ionomer and then diffused through the ionomer from the ACL's void space to reach the catalyst particle surface where it is oxidized as follows:

$$H_2 \rightarrow 2H^+ + 2e^- \tag{1}$$

Proton is transported via the ionomer next to the catalyst particles in the ACL and the membrane electrolyte layer to the cathode catalyst layer (CCL), and finally to the catalyst particles in the CCL through the ionomer covering the catalyst surface. The proton transport through the ionomer and the membrane electrolyte accompanies the transport of water along with it, a phenomenon often referred to as the electroosmotic drag effect. Also proton conductivity is highly sensitive to the water content in the ionomer and the membrane, that is related to the water absorption/desorption, transport via diffusion (without pressure differential between the anode and cathode) and hydraulic permeation (in the presence of pressure differential).

Meanwhile electron is transported via the solid conducting particles (catalyst and its support) in the ACL to the GDL, and then via the conducting flow channel ribs and anode bipolar plate to the external circuit, doing electric work before arriving at the cathode. Then electron is transported through the cathode bipolar plate and the cathode flow channel ribs to the cathode GDL, and finally reaches the catalyst particles in the CCL. At the same time, oxygen (or air) through the flow channels built on the cathode flow distribution (or bipolar) plate is supplied to the cathode with its major flow direction parallel the cathode electrode surface. Through the combined effect of convection and diffusion, oxygen is transported through the cathode GDL to the void space in the CCL, dissolved into the ionomer and then diffused through the ionomer from the CCL's void space to the catalyst particle surface where it is reduced via the following cathode reaction:

$$\tfrac{1}{2}\,O_2 + 2H^+ + 2e^- \rightarrow H_2O + \text{waste heat} \tag{2}$$

It might be mentioned that due to the sensitivity of the platinum catalyst to the presence of impurities, the feed gases (both fuel and