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An engineering approach to optimal metallic bipolar plate designs reflecting gas diffusion layer compression effects

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ABSTRACT

GDL (Gas diffusion layer) intrusion into gas feeding channels narrows the effective channel cross-sectional area and eventually results in performance degradation of PEFCs (polymer electrolyte fuel cells). Therefore, cross-sectional channel design of metallic bipolar plates should be optimized to resolve this problem. In this study, effects of the cross-sectional configuration of metallic gas channels on pressure drops are numerically investigated for the comprehensive fluid dynamic analysis of channel flow. Multi-physics numerical systems combining solid mechanics and fluid dynamics are applied to figure out the GDL behavior. First, static structural analysis is performed to determine elastic deformation of GDLs under clamping forces. Subsequently, computational flow analysis in the deformed regions is conducted to visualize flow patterns and estimate corresponding pressure drops. Four cross-sectional parameters are selected: channel to rib width ratio, draft angle, inner fillet radius and clamping pressure. Results are validated against experimental data. The GDL intrusion is found to be greatly affected by draft angle and channel to rib ratio. Cross-sectional area is reduced down to 45% in the most shrunk channel, leading additional pressure drop of 0.12 bar. It is suggested that fluid dynamics should be combined with solid mechanics for better accuracy in computational fuel cell modeling.

1. Introduction

High density graphite has been widely used as primary material for bipolar plates. Graphite has excellent chemical and electrical characteristics. However, graphite is brittle and permeable to gases from the mechanical point of view. Moreover, CNC (computer numerical control) fabrication of graphite bipolar plates is less competitive in time and cost. Recently, a lot of technical attention has been paid to metallic bipolar plates due to its flexibility and low gas permeability. Metallic bipolar plates can significantly reduce the volume of fuel cell stacks and have high thermal and electrical conductivities. In addition, relatively simple fabrication process of gas channels on the metallic plates by stamping enables mass production. In spite of these technical benefits, metallic plates are highly susceptible to corrosion which is closely related to reliability and durability of fuel cell engines [1,2].

Remarkable difference between graphite and metallic bipolar plates for fuel cell applications is cross-sectional channel designs. CNC machining can precisely engrave a rectangular channel cross-section along the in-plane direction flow direction, whereas stamping metallic plates forms a trapezoidal cross-section of gas feeding channels.

GDLs (gas diffusion layers) adjacent to bipolar plates deliver reactant gases to catalyst layers thorough void spaces and plays a vital role in heat and water management of fuel cells. GDLs are made with deformable porous carbon materials [3]. Bipolar plates and GDLs are under very high pressure during stacking processes of fuel cells. GDLs absorb the stacking stress and deforms in shape, intruding into gas feeding channels on bipolar plates. Particularly, this intrusion shrinks flow field cross-section areas of fuel and oxidant supplying channels and increases flow velocity in gas channels and resultant pressure drop [4–6].

Many researchers have studied the effect of GDL compression on PEFC (polymer electrolyte fuel cell) performance. Kandlikar et al. [7] analyzed uneven GDL intrusion in gas channels on graphite plates and its effects on flow distribution with both experimental and computational analysis. Taymaz [8] numerically studied the optimum range of the assembly pressure from the calculated species fractions, species velocities and the performance curves. Zhou [9] numerically simulated the influence of the GDL deformation. They showed that PEFCs debase with increased clamping compression. Large GDL compression and large porosity difference lessen the transport capability of the reactant and water. Su et al. [10] studied the effects of compression force on cell capacity

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Nomenclature

A	cross-sectional area
CR	channel to rib ratio
D	diameter, [m]
E	Young's modulus, [MPa]
L	rib length, [mm]
P	pressure, [Pa]
R	inner fillet radius, [mm]
Re	the Reynolds number
u	velocity, [m s^{-1}]
W	channel width, [mm]
Greek letter	
ε	normal strain rate
μ	gas viscosity, [kg m^{-1} s^{-1}]
ν	Poisson's ratio
θ	draft angle, [°]
ρ	density, [kg m^{-3}]
σ	normal stress, [N m^{-2}]
τ	shear stress, [N m^{-2}]
Subscripts	
c	clamping pressure
ch	channel
h	hydraulic property
m	momentum
w	properties at a wall

numerically. They focused on the distribution of GDL characteristics on cell capacity and the effects of cross-channel drift brought by pressure gradient between channels. The effect of reactants and coolant channel designs are of great interest in performance analyses of PEFCs [11–13]. Hernandez et al. [14] investigate fuel cell performance using a spiral flow distributor. While most of aforementioned studies investigated GDL compression on graphite bipolar plates, comparatively little attention has been paid to details of the intrusion phenomenon on metallic bipolar plates. Turan [15] studied the effects of manufacturing on metallic bipolar plate, however limited to the fabrication method of plates. The channel structure should be optimized for the genuine article molding and application of metallic bipolar plate.

In this study, the influence of the metallic channel cross-sectional configuration on performance of PEFCs is investigated numerically and experimentally. Multi-physics numerical systems combining solid mechanics and fluid dynamics are applied to figure out the GDL intrusion with various geometrical parameters. First, static structural analysis is performed to determine elastic deformation of GDLs under clamping forces. Subsequently computational flow analysis with the deformed fuel cell domains is conducted to visualize flow patterns and estimate corresponding pressure drops. Four cross-sectional parameters are selected: channel to rib width ratio, draft angle, inner fillet radius and clamping pressure.

2. Numerical study of GDL intrusion and flow characteristics in shrunk channels

Fig. 1 shows the notable difference between graphite and metallic bipolar plates by schematic diagrams of channel cross-sections. For the rectangular channel cross-section of graphite bipolar plates, we can set channel to rib ratio and clamping pressure as primary channel design parameters. In contrast, metallic bipolar plates have trapezoidal channel cross-section due to stamping methods. Draft angle and inner fillet radius are added as additional channel design parameters. All design parameters are listed in Table 1.

For modeling purpose, a computational static structural program, ANSYS®, is used to determine the extent of GDL deformation. In sequence, comprehensive computational flow analysis in deformed fluid regions is conducted by using a commercial fluid dynamic software (FLUENT®) to predict pressure drops along the gas channels.

2.1. Numerical model assumption

The present model assumes:

- linearly elastic and isotropic gas diffusion layers
- negligible Darcy's drag through porous GDLs
- incompressible and laminar flow due to low Reynolds number, and
- constant temperature and mechanical properties

2.2. Governing equations

2.2.1. Elastic theories for GDL intrusion

The mechanical behavior of GDL, under the above-mentioned assumptions, can be modeled by static equilibrium equation and stress–strain constitutive equation, in the vector form, as follows:

$$\nabla \cdot \vec{\sigma} + \rho g = 0 \tag{1}$$

$$\vec{\sigma} = E\vec{\varepsilon} \tag{2}$$

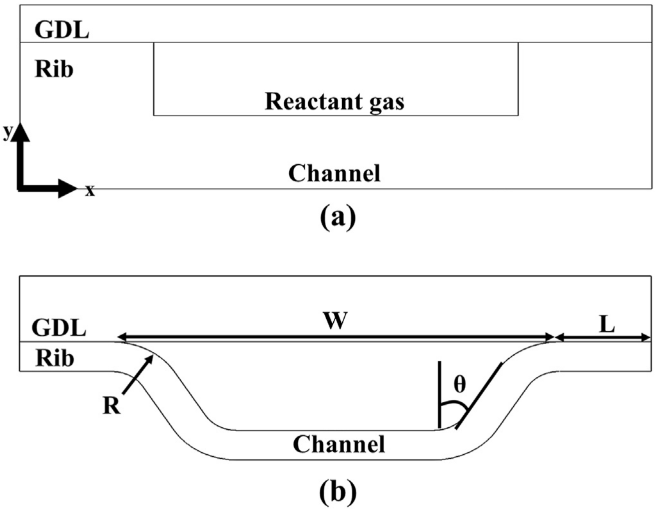

Fig. 1. Schematic diagrams of gas channel cross-section (a) in a graphite bipolar plate and (b) in a metallic bipolar plate.