Non-isothermal transport phenomenon and cell performance of a cathodic PEM fuel cell with a baffle plate in a tapered channel

Shiang-Wuu Perng a, Horng-Wen Wu b, *

a Department of Accounting Information, Kun Shan University, No. 949, Da Wan Rd., Yung-Kang City, Tainan Hsien, 710, Taiwan, ROC
b Department of Systems and Naval Mechatronic Engineering, National Cheng Kung University, Tainan, Taiwan, ROC

Abstract

This study uses a projection finite element analysis with an element-by-element preconditioned conjugate gradient method to investigate the non-isothermal tapered flow channel installed with a baffle plate for enhancing cell performance in the cathodic side of a PEMFC. The parameters studies including tapered ratio (0.25 ~ 1.0) and gap ratio (0.005 ~ 0.2) on the cell performance have been explored in detail. The results indicate that the stronger composite effect of tapered flow channel and baffle blockage provides a better convection heat transfer performance and a higher fuel flow velocity and thus enhances the cell performance.

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1. Introduction

Due to their operating temperature, high energy efficiency and economic features, proton exchange membrane fuel cells (PEMFCs) have been considered as a potential candidate of the power sources in the future [1,2]; their potential has, for instance, been demonstrated in the Ballard transit bus [3]. Design of the flow channel in bipolar plates is important for the cell performance of a PEMFC system. In the past two decades, a lot of studies have been endeavored to various flow channels in PEMFC systems such as the arrangements of serpentine channel, multiple channels in parallel type, interdigitated channels, and other channels. The fuel flow channel has a gas diffusion layer (GDL) as a side-wall, so that the GDL morphology may influence the reactant gas transport from channel to the catalyst surface and the cell performance. Wang et al. [4] designed two novel biometric flow slabs to enhance the capability of oxygen transportation and promote the liquid water removal. Hence, its possession of a higher flow uniformity and lower pressure drop would produce a better power performance than the serpentine and parallel flow. Henriques et al. [5] used Comsol Multiphysics to develop a three-dimensional model of the original PEM fuel cell with parallel plus a transverse flow channel design, including the effects of liquid water formation and electric current production. Using this model, they studied how different channel geometries and respective cathode flow rates affected the cell’s performance. For the performance of a PEMFC, the cathode is regarded as the dominant component. This idea is due to the slow kinetics of oxygen reduction [6] and the cell performance depends strongly on the oxygen transport rate to the cathode. Jordan et al. [7] explained how the GDL morphology influenced the cell performance by conducting experiments with a model of hydrophobicity. Therefore, the modeling of the cathodic half-cell of a PEMFC has been emphasized [7–12].

The physical problems involved in the operation of a PEMFC are highly complex and poorly understood. Accordingly, the increasing numbers of researchers [13–16] have employed CFD simulations to flow distribution and fuel gas diffusion in a PEMFC recently. Perng et al. [13] numerically investigated the installation of a transverse rectangular cylinder along the gas diffusion layer (GDL) in the flow channel for enhancing cell performance of a proton exchange membrane fuel cell (PEMFC). The results showed that the transverse installation of a rectangular cylinder in the fuel flow channel enhanced the cell performance of a PEMFC effectively. In addition, the width of the cylinder influenced the cell performance obviously. Wang et al. [14] developed a two-dimensional numerical model to study the two-phase flow transport in the air cathode of a PEMFC. In this paper, the model encompassed both single- and two-phase regimes corresponding to low and high current densi-
ties and could predict the transition between the two regimes. Wu et al. [15] performed a steady and unsteady 3D non-isothermal modeling of PEM fuel cells to investigate the non-equilibrium membrane water absorption/desorption processes along with non-equilibrium condensation/evaporation processes. Baschuk and Li [16] developed an isothermal, steady state, two-dimensional model that were used as the general formulation for the simulation and analysis of PEM fuel cells. Water was assumed to be in either the gas phase or a liquid phase in the pores of the polymer electrolyte. The results showed three phenomena: the gas phase transport in the gas flow channel, electrode backing and catalyst layers; the gas transport of water in the gas and electrolyte phases in the catalyst and polymer electrolyte layers; and the effect of channel length on the performance of a PEM fuel cell. Perng and Wu [17] found how internal flow modification enhanced the cell performance of a proton exchange membrane fuel cell (PEMFC). The results indicated that the dramatic degradation of the local current density in the downstream region of a blocked channel reflected the more efficient fuel transport and the chemical reaction in the upstream. Consequently, these two counter-effects render the resultant current density or performance of the fuel cell insensitive to the application of baffles. The present study therefore employs the tapered design of the flow channel to reduce the reflection effectively for enhancing the local cell performance. In addition, many studies [13,16–21] in last 5 years used two-dimensional model to simulate the gas transport and investigate the cell performance in the PEMFC, for saving the computational mesh and CPU time with the reasonable prediction.

There were a number of studies on enhancing the cell performance of the PEMFC for various configurations of fuel flow channel but few reports on the influence of the tapered flow field with various outlet heights and gap sizes applied to the fuel flow channel [17], the enhancement technique investigated here is to employ a baffle plate for generating the blockage effect on the non-isothermal fuel flow in the channel, and the tapered design of channel to reduce effectively the reflection caused by the baffle plate in the down-
stream region. Examining the efficacy of the enhancement technique for the cell performance of a PEMFC is a motivation to us from practical consideration. The purpose of this paper is to quantify numerically how a baffle plate in non-isothermal tapered flow field enhances the cell performance while changing tapered ratio and gap ratio in the fuel flow channel. According to the results in the Refs. [18,21], the effect of liquid water is only significant at low voltage conditions and the liquid water effect does not change the trend of fuel cell performance enhanced by the internal flow modification. Therefore, the two-phase effect is neglected in the model to investigate how baffle plate and tapered flow channel influences the cell performance enhancement of a PEMFC. This paper describes a semi-implicit finite element study with an element-by-element preconditioned conjugate gradient method that investigated the blocking effect generated by a baffle plate in the non-isothermal tapered flow channel and how it affects the cell performance of a PEMFC when changing the cathodic over-potential. Semi-implicit finite element analysis with the projection technique proposed by Ramaswany et al. [22,23] is a powerful numerical method for unsteady incompressible flows. Also, this study incorporated an iterative solution method on the basis of the element-by-element preconditioned conjugate gradient method [24] into the solving process to require much less computer storage and CPU time than the conventional finite element methods. The results of this paper may be of interest to engineers attempting to develop the optimization of a PEMFC and to researchers interested in the flow modification aspects of the PEMFC performance enhancement in the cathode.

2. Model development

In the present paper, the physical problem involves a two-dimensional half-cell model of the PEMFC system including the mass, momentum, energy, and concentration transport of fuel gas in the flow channel and the porous GDL at the cathode as shown in Fig. 1. Although the flow channel maybe hundreds of mm for both experiments and applications, for saving the computational mesh and CPU time, the length of the flow channel was set to be 10 mm with the ratio of channel length to height equal to 20. In addition, the ratio of channel length to height equal to 20 is enough for the fully developed flow field. The geometrical relations in this study are set forth: \( H_1/H = 0.4, L_1/H = 20, L_1/H = L_2/H \). Two parameters used are the tapered ratio \( (H_2/H) \) and the gap ratio \( (\lambda = H_2/H) \). Furthermore, the gap ratio is ranged from 0.005 to 0.2, and the tapered ratio is taken as 0.25, 0.5 and 1.0. The model of this study is subject to the following assumptions:

1. The gas behaves according to the ideal gas model.
2. The fluid flow is unsteady, laminar, and incompressible; all the physical properties of the fluid are taken to be constant.
3. Porous GDL is homogeneous and isotropic with uniform morphological properties.
4. Water in the electrode exists as vapor only.
5. Catalyst layer is considered to be an ultra-thin layer, and the fast and complete reaction of oxygen thus occurs only on the surface of the catalyst layer.

The two-dimensional governing equations for the fuel flow channel and gas diffusion layer in a half-cell of the PEMFC are:

\[
\nabla \cdot (\rho \frac{\partial \mathbf{u}}{\partial t}) = 0 \tag{1}
\]

\[
\frac{\partial \mathbf{u}^*}{\partial t} + (\mathbf{u}^* \cdot \nabla) \mathbf{u}^* = -\frac{1}{\rho_f} \mathbf{p}_f - \frac{\mu}{\rho_f} \nabla^2 \mathbf{u}^* - \frac{\mu}{\rho_f} \mathbf{e} \nabla T^* \tag{2}
\]

\[
(\rho c_p)_{eff} \frac{\partial T^*}{\partial t} + (\rho c_p)_{eff} (\mathbf{u}^* \cdot \nabla) T^* = k_{eff} \nabla^2 T^* \tag{3}
\]

\[
\frac{\partial c_i^*}{\partial t} + (\mathbf{u}^* \cdot \nabla) c_i^* = D_{i eff} \nabla^2 c_i^* \tag{4}
\]

Fig. 1. Schematic of the physical domain for a PEMFC half-cell in a: (a) normal channel without a baffle plate and (b) tapered channel with a baffle plate.
Table 1
Geometric and physical parameters used in this study.

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flow channel length, l (mm)</td>
<td>10</td>
</tr>
<tr>
<td>Flow channel height, H (mm)</td>
<td>0.5</td>
</tr>
<tr>
<td>Gas diffusion layer thickness, H (mm)</td>
<td>0.2</td>
</tr>
<tr>
<td>Baffle plate width, L (mm)</td>
<td>0.1</td>
</tr>
<tr>
<td>Inlet temperature, T_e (K)</td>
<td>323</td>
</tr>
<tr>
<td>Operating pressure (atm)</td>
<td>1</td>
</tr>
<tr>
<td>Faraday constant, F (C mol⁻¹)</td>
<td>96,487</td>
</tr>
<tr>
<td>Permeability of gas diffusion layer, κ (m²)</td>
<td>1.0 x 10⁻¹²</td>
</tr>
<tr>
<td>Universal gas constant, R (mol⁻¹ K⁻¹)</td>
<td>8.314</td>
</tr>
<tr>
<td>Ohmic resistance, R (Ω cm⁻²)</td>
<td>0.16</td>
</tr>
<tr>
<td>Open circuit voltage, V_o(V)</td>
<td>1.1</td>
</tr>
<tr>
<td>Electrochemical coefficients, x</td>
<td>0.6</td>
</tr>
<tr>
<td>Porosity of the gas diffusion layer, ε</td>
<td>0.4</td>
</tr>
<tr>
<td>Tortuosity of the gas diffusion layer, τ</td>
<td>1.5</td>
</tr>
<tr>
<td>Inlet average velocity, u_in (m s⁻¹)</td>
<td>0.25</td>
</tr>
<tr>
<td>Relative humidity of inlet oxygen</td>
<td>0%</td>
</tr>
<tr>
<td>Exchange current density, i_c (A m⁻²)</td>
<td>100</td>
</tr>
<tr>
<td>Reference oxygen concentration at inlet, c_o,ref (mol m⁻³)</td>
<td>35.7</td>
</tr>
<tr>
<td>Fluid viscosity, μ (kg cm⁻¹ s⁻¹)</td>
<td>0.21 x 10⁻⁶</td>
</tr>
</tbody>
</table>

where $\vec{u}$ is the velocity vector, $\rho$ the fluid density, $\mu$ the fluid viscosity, $C_p$ the specific heat capacity, $k$ the thermal conductivity, $c_i$ the fluid concentration and $D_{i,\text{eff}}$ the effective diffusivity. In addition, the effective diffusivity $D_{i,\text{eff}}$ is modified by the Brugman correlation [25] for the effects of porosity and tortuosity ($\tau$) in the porous electrode, i.e.,

$$D_{i,\text{eff}} = \epsilon^\tau D_{i,\text{ref}}$$

where the tortuosity ($\tau$) of 1.5 was used for the investigation of reactant gas transport in the mainstream flow channel of a PEMFC in this study.

The governing equations are normalized by first defining dimensionless independent variables of the form $x = x^*/H$, and $y = y^*/H$. Moreover, dependent dimensionless variables may also be defined as $\bar{u} = u' / u_{in}$, $t = (\tau u_{in}) / H$, $p = p' / (\rho u_{in}^2)$, $Da = \kappa / H^2$, $Re = (u_{in}H)/v$, and $Sc = v/D_{i,\text{eff}}$, the above governing equations are written in the non-dimensional form:

$$\nabla \cdot \bar{u} = 0$$

$$\frac{\partial \bar{u}}{\partial t} + (\bar{u} \cdot \nabla) \bar{u} = - \nabla p + \frac{1}{Re} \nabla^2 \bar{u} - \frac{1}{Re Da} \epsilon \bar{u}$$

$$\frac{\partial c_i}{\partial t} + (\bar{u} \cdot \nabla) c_i = \frac{1}{ReSc} \nabla^2 c_i$$

The momentum equations are valid in both the porous gas diffusion layer and the fuel flow channel. They are reduced to the extended Darcy’s law for flow in the porous cathode with a small permeability [25], and become the Navier–Stokes equations inside the flow channel with the porosity of unity and the permeability of infinite.

In the computational domain, the initial conditions are $u = v = T = c_{O_2} = c_{H_2,O} = 0$ for $t = 0$. The following boundary conditions are specified for computations as shown in Fig. 1 [26,27].

(a) At the oxygen inlet (BC1):

$$u_1 = 1, u_2 = 0, T = 1, c_{O_2} = c_{O_2,\text{in}}, c_{H_2,O} = c_{H_2,O,\text{in}}$$

(b) At the both sides of the GDL (BC2 and BC5):

$$\text{Kazim and others' predictions}$$

$$\text{The present predictions}$$

Fig. 2. (a) Mesh sensitivity and (b) time step size sensitivity of local current density distribution on the surface of the catalyst layer for the normal channel without a baffle plate.

Fig. 3. Comparison of the results between the present prediction and Kazim and other’s prediction.
\[ u_1 = u_2 = \frac{\partial T}{\partial x} = \frac{\partial C_{O_2}}{\partial x} = \frac{\partial C_{H_2O}}{\partial x} = 0 \]  
\( (12) \)

(c) On the faces of the baffle plate (BC7 ~ BC9):

\[ u_1 = u_2 = \frac{\partial T}{\partial n} = \frac{\partial C_{O_2}}{\partial n} = \frac{\partial C_{H_2O}}{\partial n} = 0 \]

\( (13) \)

(d) On the current collector surfaces (BC3):

\[ u_1 = u_2 = \frac{\partial T}{\partial y} = \frac{\partial C_{O_2}}{\partial y} = \frac{\partial C_{H_2O}}{\partial y} = 0 \]

\( (14) \)

(e) At the outlet (BC4):

\[ \frac{\partial u_1}{\partial x} = \frac{\partial u_2}{\partial x} = \frac{\partial T}{\partial x} = \frac{\partial C_{O_2}}{\partial x} = \frac{\partial C_{H_2O}}{\partial x} = 0 \]

\( (15) \)

(f) On the surface of the catalyst layer (BC6):

\[ u_1 = u_2 = \frac{\partial p}{\partial y} = 0; \quad -k \frac{\partial T}{\partial m} = I \left( \eta - \frac{T_m \lambda S}{nF} \right) \]

\( (16) \)

Regarding the boundary conditions of the reactant concentrations on the surface of the catalyst layer, this study employed the Butler–Volmer correlation [27] for the rate of electro-chemical reaction on the surface relating the local current density to the reactant concentrations:

\[ I_x = I_0 \left[ \left( \frac{C_{O_2}}{C_{O_2,ref}} \right) \exp \left( \frac{4\alpha F}{RT} \eta \right) \right] \]

\( (17) \)

\( \alpha \) is the electrochemical coefficient depending on the exchange current density and the over-potential on the electrode surfaces. In this paper, it is considered to be constant. In Eq. (17), the first term is the reductive current representing the strength of forward reaction, while the second term is the oxidative current that has an opposed effect on the oxygen reduction reaction (ORR). According to the equation \( O_2 + 4H^+ + 4e^- \rightarrow 2H_2O \), the oxygen consumed rate on the reaction surfaces by the ORR should equal the produced current. Therefore, the balance of the oxygen concentration on the reaction boundary is:

\[ -D_{O_2,eff} \frac{\partial C_{O_2}}{\partial y} = \frac{I_x}{4F} \]

\( (18a) \)

\[ D_{H_2O,eff} \frac{\partial C_{H_2O}}{\partial y} = \frac{I_x}{2F} \]

\( (18b) \)

Fig. 4. Local current density distributions along the catalyst surface for various tapered ratios of flow channel without a baffle plate: (a) \( \eta = 0.4 \) and (b) \( \eta = 0.9 \).

Fig. 5. Local current density distributions along the catalyst surface for various tapered ratios of flow channel at \( \lambda = 0.2 \) and: (a) \( \eta = 0.4 \) and (b) \( \eta = 0.9 \).
According to Eqs. (17) and (18), this study obtains the Eq. (19).

\[ D_{\text{O}_2,\text{eff}} \left( \frac{\partial C_{\text{O}_2}}{\partial y} \right) + \frac{l_0}{4F} \left( \frac{C_{\text{O}_2}}{C_{\text{O}_2,ref}} \right) \exp \left( \frac{4\sigma F}{RT} \eta \right) = 0 \]  
\[ (19a) \]

\[ D_{\text{H}_2\text{O,eff}} \left( \frac{\partial C_{\text{H}_2\text{O}}}{\partial y} \right) + \frac{l_0}{2F} \left( \frac{C_{\text{H}_2\text{O}}}{C_{\text{H}_2\text{O},ref}} \right) \exp \left( \frac{4\sigma F}{RT} \eta \right) = 0 \]  
\[ (19b) \]

After the non-dimensional process is taken, the non-dimensional boundary conditions are expressed as:

\[ \frac{\partial C_{\text{O}_2}}{\partial y} + R_{\text{M}1} C_{\text{O}_2} = 0 \]  
\[ (20a) \]

\[ \frac{\partial C_{\text{H}_2\text{O}}}{\partial y} + R_{\text{N}1} C_{\text{O}_2} = 0 \]  
\[ (20b) \]

where the non-dimensional parameters described are as follows:

\[ R_{\text{M}1} = \frac{l_0 H \cdot \exp \left( \frac{4\sigma F}{RT} \eta \right)}{4FC_{\text{O}_2,ref} D_{\text{O}_2,\text{eff}}} \]  
\[ (21a) \]

\[ R_{\text{N}1} = \frac{l_0 H \cdot \exp \left( \frac{4\sigma F}{RT} \eta \right)}{2FC_{\text{H}_2\text{O},ref} D_{\text{H}_2\text{O},\text{eff}}} \]  
\[ (21b) \]

Fig. 6. Local current density distributions along the catalyst surface for various tapered ratios of flow channel at \( \lambda = 0.005 \) and: (a) \( \eta = 0.4 \) and (b) \( \eta = 0.9 \).

Fig. 7. The local distributions of oxygen mass fluxes along the catalyst surface for various tapered ratios of flow channel: (a) no baffle plate, (b) \( \lambda = 0.2 \), and (c) \( \lambda = 0.005 \).
Fig. 8. Local distributions of velocity vectors for various tapered ratios of flow channel without a baffle plate: (a) $R_{ch} = 1.0$, (b) $R_{ch} = 0.5$, and (c) $R_{ch} = 0.25$.

Fig. 9. Local distributions of velocity vectors for various tapered ratios of flow channel at $k = 0.2$: (a) no baffle plate, (b) $R_{ch} = 1.0$, (c) $R_{ch} = 0.5$, and (d) $R_{ch} = 0.25$. 
3. Numerical details

This study uses the Galerkin finite element method to treat with the conservation equations in spatial discretization, which produces linear equations solved iteratively by an element-by-element preconditioned conjugate gradient method. When the finite element discretized, the unknown physical variables \( u, p, T \) and \( c \) are approximated by:

\[
    u_i = \phi_a u a_i, \quad p = \phi_a p a, \quad T = \phi_a T a, \quad c = \phi_a c a.
\]

The corresponding weighting functions are:

\[
    u_i = \phi_a u a_i; \quad p = \phi_a p a; \quad T = \phi_a T a; \quad c = \phi_a c a.
\]

In which subscripts \( a \) denotes node and \( i \) refers to direction. The \( \phi_a \) is the interpolation function. Then Eqs. (7)–(10) become:

\[
    H_{ab} u_b = 0 \quad (22)
\]

\[
    M_{ab} \frac{du_b}{dt} + H_{ab} p_b + \frac{1}{Re} S_{abj} u_j u_b = -\frac{\varepsilon}{Re Da} M_{ab} u_b \quad (23)
\]

\[
    M_{ab} \frac{dT_b}{dt} + \frac{1}{Re Pr} A_{abj} T_j + K_{abj} u_j T_b = \frac{1}{Re Pr} \sum_{x \in T} \quad (24)
\]

\[
    M_{ab} \frac{dc_b}{dt} + \frac{1}{Sc Re} A_{abj} c_j + K_{abj} u_j c_b = \frac{1}{Sc Re} \sum_{x \in T} \quad (25)
\]

The concept of projection consists of a second-order Adams–Bashforth scheme for the advection terms and an implicit Euler scheme for the diffusion terms. The solution procedure is as follows:

**Step 1**

This step is to determine an intermediate velocity field \( \vec{u}^{n+1} \) from \( \vec{u}^n \) for \( n = 0 \), using the explicit Adams–Bashforth scheme for the advection terms and an implicit Euler scheme for the diffusion terms. The solution procedure is as follows:

**Table 2**

Dimensionless pressure drop between gas fuel inlet and outlet in the channel.

<table>
<thead>
<tr>
<th>No baffle plate</th>
<th>( \lambda = 0.2 )</th>
<th>( \lambda = 0.005 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( R_{ch} = 1.0 )</td>
<td>16.74</td>
<td>86.02</td>
</tr>
<tr>
<td>( R_{ch} = 0.5 )</td>
<td>697.45</td>
<td>926.71</td>
</tr>
<tr>
<td>( R_{ch} = 0.25 )</td>
<td>1067.45</td>
<td>1221.48</td>
</tr>
</tbody>
</table>

**Fig. 10.** Local distributions of velocity vectors for various tapered ratios of flow channel at \( \lambda = 0.005 \): (a) no baffle plate, (b) \( R_{ch} = 1.0 \), (c) \( R_{ch} = 0.5 \), and (d) \( R_{ch} = 0.25 \).
forth method for the nonlinear convective term and a first-order implicit Euler time integration scheme for the diffusion term.

\[
M_{ab}u^{n+1}_{i} = M_{ab}u^{n}_{i} - \frac{\Delta t}{\varepsilon} \left( \frac{3}{2} K_{bji} (\varepsilon t) u^{n}_{i} - \frac{1}{2} K_{bji} u^{n-1}_{i} u^{n-1}_{i} \right) - \frac{\Delta t}{\varepsilon} \left( \frac{3}{2} K_{bji} (\varepsilon t) u^{n}_{i} - \frac{1}{2} K_{bji} u^{n-1}_{i} u^{n-1}_{i} \right)
\]

\[
\frac{\Delta t}{\varepsilon} \sum_{j} K_{bji} u^{n+1}_{j} - \frac{\varepsilon \Delta t}{Da_{ab}} M_{ab} u^{n+1}_{i}
\]  

(26)

Step 2

This step is to obtain pressure from a Poisson equation including \(u^{n+1}_{i}\) in the approach, only the pressure at time \(t = 0\) necessary to solve the boundary pressure Poisson equation.

\[
A_{ab}p^{n+1}_{i} = \frac{1}{\varepsilon \Delta t} M_{ab} u^{n+1}_{i}
\]

(27)

Correcting the provisional velocity with the pressure term yields the real velocity:

\[
M_{ab}^{0} u^{n+1}_{i} = M_{ab}^{0} u^{n+1}_{i} - \Delta t H_{ab} p^{n+1}_{i}
\]

(28)

where \(M_{ab}^{0}\) denotes the diagonalized mass matrix obtained simply by summing across each row of the consistent mass matrix and placing the results in the diagonal.

Step 3

Using the same procedure as the velocity phase obtains the final temperature solutions from the energy equation.

\[
M_{ab} T^{n+1}_{i} = M_{ab} T^{n}_{i} - \Delta t \left( \frac{3}{2} K_{bji} (\varepsilon t) T^{n}_{i} - \frac{1}{2} K_{bji} T^{n-1}_{i} T^{n-1}_{i} \right)
\]

\[
- \frac{\Delta t}{Re \cdot Pr} A_{ab} T^{n+1}_{i} + \frac{\Delta t}{Re \cdot Pr} \sum_{j} \frac{2}{3} K_{bji} (\varepsilon t) T^{n+1}_{j}
\]

(29)

Step 4

Employing the same procedure as the velocity phase obtains the final concentration solutions from the concentration transport equation.

\[
M_{ab} c^{n+1}_{i} = M_{ab} c^{n}_{i} - \Delta t \left( \frac{3}{2} K_{bji} (\varepsilon t) c^{n}_{i} - \frac{1}{2} K_{bji} c^{n-1}_{i} c^{n-1}_{i} \right)
\]

\[
- \frac{\Delta t}{Re \cdot Sc \cdot i} A_{ab} c^{n+1}_{i} + \frac{\Delta t}{Re \cdot Sc \cdot i} \sum_{j} \frac{2}{3} K_{bji} (\varepsilon t) c^{n+1}_{j}
\]

(30)

Using the above description about numerical methods, this study investigated the cell performance enhancement of a PEMFC by placing a baffle plate in a non-isothermal tapered flow channel at various tapered ratios (\(R_{ch} = 0.25, 0.5\) and 1.0) and gap ratios (\(k = 0.005, 0.025, 0.1\) and 0.2) when Reynolds number is kept at 15. The geometric and physical parameters employed in the present study are listed in Table 1. The test results for three finite-element meshes (10,060 nodes and 9728 elements, 13,065 nodes and 12,800 elements, 15,808 nodes and 15,487 elements) are indicated in Fig. 2a. The local current density difference between the second and the third mesh was less than 0.05% in test runs, so a finite-element mesh (13,065 nodes and 12,800 elements) was chosen in all cases. The three time steps 0.00025, 0.0005, and 0.001 were chosen.
to test the time step size sensitivity. The time increment $\Delta t$ was set at 0.0005 for all cases according to the result that the predictions between time steps at 0.0005 and 0.00025 get close in Fig. 2b. In this study, about 80,000 time steps were necessary to obtain reasonably reliable data. The CPU time was varied from 6h 49 min 28s to 7h 14 min 57s in a PENTIUM III 1G PC.

To show that the program in this study can handle the cell performance of a PEMFC, this study applied the present method to solve the oxygen gas transport through the cathode region of a PEMFC as described in Kazim and others’ paper [27]. The physical parameters and properties of the electrode are listed in Fig. 3. The mesh employed for the comparison with the reference was 4280 nodes and 3985 elements. The steady-state solution is obtained by the numerical procedure as mentioned in the previous section. As shown in Fig. 3, the result of the present predictions for the polarization curve agreeing fairly closely with Kazim and others’ [27] gives one confidence in the use of the present program.

4. Results and discussion

4.1. Current density distribution

From the results of our previous study [17], the reduction of the local current density reflects more efficient fuel transport and the chemical reaction above the baffle plate but less flows into the GDL in the downstream region behind the baffle plate. For improving the reduction of the cell performance in the downstream region, this study considers a non-isothermal tapered flow field design to reduce the reflection in the downstream region. The tapered ratio is employed to investigate how the non-isothermal tapered flow channel affects reactant fuel gas and cell performance of a PEMFC. The local current density along the catalyst layer at the steady state is calculated with Eq. (18a) about 80,000 time steps. Fig. 4 indicates how tapered ratio influences the local current density for the normal channel (without a baffle plate) at the over-

![Fig. 12. The local distributions of dimensionless oxygen concentration for various tapered ratios of flow channel at $\lambda = 0.2$: (a) no baffle plate, (b) $R_{ch} = 1.0$, (c) $R_{ch} = 0.5$, and (d) $R_{ch} = 0.25$.](image)
potential conditions of 0.4 and 0.9. From the ordinates in Fig. 4a and b, the variations in the local current density along the main-flow direction are relatively more noticeable at the over-potential condition of 0.9 (Fig. 4b). The electro-chemical reaction in the catalyst layer is expected to be stronger at a lower operating voltage or a higher operating current density. Consequently, the reactant oxygen consumes at a higher rate when it flows along the main-flow direction, which in turn obtains the substantial variations in the local current density. In addition, Fig. 4 reveals that the local current density is enhanced better for the fuel channel with a smaller tapered ratio $R_{ch}$. In other words, a smaller $R_{ch}$ causes the better cell performance of a PEMFC. How the non-isothermal tapered flow channel with a baffle plate affects the local current density is found in Figs. 5 and 6. The qualitative trend of the curves in Figs. 5 and 6 is interpreted in the same way as the case of flow channel without a baffle plate in Fig. 4, except for the peak region at the region between $x' = 4.85$ mm and $x' = 5.07$ mm around the baffle plate. The major difference is that the local current density in Fig. 4 is enhanced by the tapered flow via a decrease in the outlet height of flow channel, whereas the local current density or cell performance in Figs. 5 and 6 is enhanced by the composite effect of a tapered flow channel and a baffle plate blockage. Therefore, the composite effect not only reduces the reflection in the downstream region to enhance the local current density but also enhances the local current density in the peak region ($x' = 4.85$ mm $\sim x' = 5.07$ mm) around the baffle plate. From a comparison between Figs. 5 and 6, the best enhanced local current density occurs at the gap ratio of 0.005 and the tapered ratio of 0.25, while the worst enhancement occurs at the gap ratio of 0.2 and the tapered ratio of 1. This result is since the smaller gap forces more fuel gas to run into the gas diffusion layer (GDL), and the tapered channel with a smaller $R_{ch}$ accelerates and forces the fuel gas into the GDL. In the upstream region before the baffle plate, the profile of the local current density is slightly enhanced because there is only the tapered effect.

![Diagram](image1)

![Diagram](image2)

![Diagram](image3)

![Diagram](image4)

**Fig. 13.** Local distributions of dimensionless oxygen concentration for various tapered ratios of flow channel at $\lambda = 0.005$: (a) no baffle plate, (b) $R_{ch} = 1.0$, (c) $R_{ch} = 0.5$, and (d) $R_{ch} = 0.25$. 
However, in the downstream region behind the baffle plate, the composite effect increases the distribution of the local current density obviously. In Figs. 5b and 6b, the qualitative trend of the local current density at an over-potential condition of 0.9 is the same as that at an over-potential condition of 0.4.

4.2. Oxygen mass fluxes

Fig. 7 is used to indicate how the non-isothermal tapered flow channel influences the axial distribution of the oxygen mass flux along the catalyst surface to understand the distributions of the local current density clearly in Figs. 4–6. The power output is the consequence of the electro-chemical reaction so the consumption of the oxygen along the catalyst layer is regarded as an index of the cell performance. A higher mass flow flux indicates a higher current density, i.e., a better cell performance. The oxygen decreases generally along the catalyst (with an increase in the axial coordinate x) but a sudden rise occurs around the baffle plate as shown in Fig. 7b and c. This sudden rise is caused by the strong forced convection, which enhances the transport of the oxygen. The sudden rise increases obviously when the tapered ratio $R_{ch}$ increases. With a smaller $R_{ch}$, the oxygen mass fluxes increase more obviously in the downstream region than in the upstream region. This phenomenon is caused by the composite effect of a tapered channel and a baffle plate blockage, which exists in the downstream, and the reflection exists scarcely here. Furthermore, the maximum profile of the oxygen mass flux occurs at the gap ratio of 0.005 and the tapered ratio of 0.25 because of the strong tapered and blockage influences. These results of Fig. 7 give one confidence in the results of Figs. 4–6.

4.3. Velocity field

To understand the non-isothermal fuel flow field and water management of the tapered flow channel, this paper employs Figs. 8–10 to display the local distributions of the velocity vectors for various tapered flow channels with or without a baffle plate at $Re = 15$ and $\eta = 0.4$. The reactant fuel gas in the tapered flow channel is accelerated and forced into the gas diffusion layer in Fig. 8b and c. Furthermore, the velocity is obviously higher in a tapered flow channel with a smaller $R_{ch}$, and the tapered flow becomes stronger with a decrease in the value of $R_{ch}$. The stronger tapered influence thus enhances the electro-chemical reaction, and removes water more effectively. In Fig. 9, the stronger flow produces a higher velocity in the GDL and a stronger vortex around the corner behind the baffle plate at the ample gap size ($z = 0.2$). This vortex helps the gas flow move into the gas diffusion layer in the downstream region. In Fig. 10, there is not a vortex around the corner behind the baffle plate at the narrow gap size but the composite effect of tapered flow and stronger blockage reduces the deflecting phenomenon effectively. From a comparison between Figs. 9 and 10, the composite effect is more obvious to reduce the deflecting phenomenon at the gap ratio of 0.005 than at the gap ratio of 0.2 so the stronger forced convection enhances the transport of the oxygen at the gap ratio of 0.005. The stronger composite effect thus enhances the local current density possibly.
These flow characteristics demonstrates the profiles of the local current density and the oxygen mass fluxes as indicated in Figs. 4–7. Water is the product of the reaction at the surface of the catalyst layer, and the maximum water vapor concentration can therefore occur at the interface of the GDL and the catalyst layer where the oxygen is consumed. From the results of Figs. 9 and 10, the stronger composite effect of tapered flow and stronger blockage generates the stronger forced convection to remove the excess water. This phenomenon was also describes in the previous study [18].

4.4. Pressure drop in the channel

For understanding how tapered flow channel and baffle plate affects the pressure drop, Table 2 presents the dimensionless pressure drop between gas fuel inlet and outlet across the channel, \( \Delta p = (p_{\text{inlet}} - p_{\text{outlet}}) \), for various conditions. From the results of Table 2, this design improves the fuel transport rate and enhances the reaction at the catalyst layer, however, this arrangement of channel produces larger pressure-loss and needs higher pumping power for the delivery of the fuel. Therefore, with an appropriate gap and tapered ratios, e.g., \( \lambda = 0.2 \) and \( R_{ch} = 0.5 \) or larger, the pressure drop and then the pumping power needs would be considerably reduced.

4.5. Concentration distribution

Figs. 11–13 reveal how various tapered flow channels with or without a baffle plate on the contours influence the oxygen concentrations. In a normal channel without the tapered effect (Fig. 11a), an area of lower oxygen concentrations generates around the rear corner in the gas diffusion layer to cause a lower
reaction rate locally at the catalyst surface and therefore a worse cell performance in the downstream region. With a smaller $R_{cb}$, the stronger tapered effect generates a larger amount of oxygen to move into the gas diffusion layer as shown in Fig. 11b and c. For the normal channel with a baffle plate as indicated in Figs. 12b and 13b, the baffle plate makes a larger amount of oxygen move into GDL but an area of lower oxygen concentrations generates around the rear corner in gas diffusion layer because of the deflecting phenomenon. For the tapered flow channel with a baffle plate as shown in Figs. 12c and d, 13c and d, a larger amount of oxygen is forced to move into the GDL around the baffle plate, and the deflecting phenomenon is reduced effectively by the tapered effect. Accordingly, the higher consumption of oxygen occurs in the GDL around the baffle plate and in the downstream region. This means that a higher reaction rate locally at the catalyst surface and a local better cell performance exist in these regions. Moreover, a higher oxygen concentration generates in the gas diffusion layer at the gap ratio of 0.005 than at the gap ratio of 0.2 because the composite effect of tapered flow and blockage is more obvious at the narrow gap size. From these results, the tapered flow channel with a baffle plate enhances the local cell performance. This phenomenon interprets the local current density distributions along the catalyst surface as indicated in Figs. 4–6.

4.6. Temperature field and overall cell performance

Figs. 14–16 show how various tapered flow channels with or without a baffle plate on the contours influence the temperature distribution in the non-isothermal tapered flow channel. It is seen that the stronger composite effect of tapered flow and blockage results in a lower and more uniform temperature distribution in the fuel flow channel; i.e., the stronger composite effect of tapered flow and blockage obtains a better heat transfer performance of the PEMFC and reduces the cell reaction temperature. In generally,
the improvement obtained in the single-phase convection heat transfer performance in the fuel flow channel may be caused by an increasing flow interruption, a reduction in the thermal boundary layer, or an increasing velocity gradient near the GDL boundary.

The overall cell performance of a PEMFC system is understood clearly by means of plotting the polarization curve. In the polarization curves, the abscissa is the averaged current density on the catalyst surface and the ordinate is the fuel cell potential. The averaged current density on the catalyst surface is determined by:

\[ I = \frac{1}{L} \int_0^L I(x) \, dx \]  
(31)

Furthermore, neglecting the over-potential on the anode side, this study uses the following equation [27] to calculate the fuel cell potential (the operating voltage):

\[ V_{cell} = V_{oc} - \eta - I \cdot R \]  
(32)

where \( V_{oc} \) is the open circuit voltage kept constant, and the value of \( V_{oc} \) is listed in Table 1; \( \eta \) is the over-potential on the cathode side; the ohmic resistance \( R \) is set to be a constant value of 0.16 \( \Omega \) cm\(^2\) at \( T = 353 \) K throughout the electrode. Fig. 17 displays the polarization curves of the fuel cell performance various tapered flow channels with or without a baffle plate to investigate how the tapered combined with blockage affects the overall fuel cell performance. Fig. 17a indicates that at the conditions of higher operating voltages (lower over-potential on the cathode side), various tapered ratios influence the overall fuel cell performance negligibly small. However, how the tapered ratio affects the polarization curves is important at lower operating voltage conditions. Accordingly, the overall cell performance increases as the tapered ratio \( R_{ch} \) decreases, and the maximum increase in the overall cell performance is 8.24\% at \( R_{ch} = 0.25 \) and \( V_{cell} = 0.2 \) without a baffle plate. This result is since a smaller outlet height of flow channel increases the tapered effect to enhance the overall local current density along the catalyst layer, and obtains a better local cell performance there. Fig. 17b shows how the tapered channel with a baffle plate influences the overall fuel cell performance at the ample gap size (\( \lambda = 0.2 \)). A careful examination of Fig. 17b discloses that, various tapered ratios affect the overall cell performance slightly as compared with that without a baffle plate at the higher operating voltages, and the tapered ratio 0.25 attains a best overall cell performance at the lower operating voltages. Furthermore, for various tapered ratios, the maximum increase in the overall cell performance is 12.86\% at \( V_{cell} = 0.2 \) and \( \lambda = 0.2 \). This phenomenon is because the tapered ratio 0.25 forces a larger amount of fuel gas onto the GDL and the more effective reduction of the deflecting phenomenon than other tapered ratios. About the polarization curves of the fuel cell performance for different \( R_{ch} \) values at the narrow gap size (\( \lambda \) value is 0.005) as shown in Fig. 17c, the tapered ratio 0.25 obtains the best overall cell performance at the lower operating voltages, and the maximum increase in the overall cell performance is 15.48\% at \( V_{cell} = 0.2 \) and \( \lambda = 0.005 \). The maximum increase in the overall cell performance is bigger at the narrow gap size than at the ample gap size. This result is since the narrow gap size enhances the blockage effect with the tapered flow to form the stronger composite effect than the ample gap size. The tapered flow channel with a baffle plate improves the fuel transport rate and the reaction at the catalyst layer is therefore enhanced. From these results in the present study, the tapered flow channel with a baffle plate used in all cases enhances the overall cell performance of a PEMFC system, and the flow channel designs are practicable in a real PEMFC system.

Fig. 17. Effects of tapered flow channel on the polarization curves of the fuel cell performance: (a) no baffle plate, (b) \( \lambda = 0.2 \), and (c) \( \lambda = 0.005 \).
5. Conclusions

With an appropriate design of the flow channel of the bipolar plate, designers can enhance the cell performance of a PEMFC system effectively. This study has reached the end by a finite element analysis with an element-by-element preconditioned conjugate gradient method in which a non-isothermal tapered flow channel with a baffle plate was considered with various tapered ratios and gap ratios. The results of the polarization curve computed in this paper are in fair agreement with those of the reference’s predictions. The stronger composite effect of tapered flow channel and baffle blockage provides a better convection heat transfer performance and a higher fuel flow velocity, which in turn improves the local current density and polarization characteristics in a penalty of high pressure-loss. For various tapered ratios at the narrow gap size, the maximum increase in the overall cell performance is 15.48% at $V_{cell} = 0.2$ and $\lambda = 0.005$; while for tapered ratios at the ample gap size, the maximum increase is 12.86% at $V_{cell} = 0.2$ and $\lambda = 0.2$. In the whole, the tapered flow channel with a baffle plate enhances the overall cell performance of a PEMFC system.

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