HEAT TRANSFER ANALYSIS OF METAL FOAM AS REPLACEMENT FOR FLOW FIELD PLATE MATERIAL IN FUEL CELL SYSTEM

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ABSTRACT

Fuel cell is a device that converts the reactants (hydrogen and oxygen) reaction to obtain electricity and waste heat without any combustion. Single fuel cell stack consist of electrolyte membrane, catalyst media, and bipolar/end plates with flow field plate (flow channel). Flow channel has the main task to provide a channel for the reactants to the active cell area and to remove the water as by product. It also acts as a gas separator between stack unit cells. In this paper, the heat transfer phenomenon (forced convection) on metal foam (SS-316) is analyzed as flow channel in bipolar plate (single stack). Metal foam can replace the flow channel because it has less permeability that resulting for better performance compare to conventional flow channel. The metal foam also has the characteristics: light weight, stiff, good energy absorber, and able to reduce the high cost production of flow channel. The heat transfer analysis was done using forced convection formulae (Newton’s law of cooling) in porous medium to calculate: Nusselt number (Nu), coefficient of convection (hi), and heat of convection (Q). From the result, it can be concluded that the best Nu, hi, and Q between hydrogen and metal foam (SS-316) are the following: 0.06; 2.72 W/m² °C; and 0.07 W. Also the Nu, hi, and Q between oxygen and metal foam (SS-316) are: 0.16; 6.60 W/m² °C; and 0.16 W.

Keywords: Fuel cell, metal foam, SS-316, forced convection, flow field plate.
1. INTRODUCTION

Fuel cell is one of the cleanest and most efficient technologies for generating electricity. In fuel cell system there is no combustion and pollutants commonly produced by other engine. The fuel cell system only produces electricity, water, and heat. Fuel cell is an important technology for a potentially wide variety of applications including on-site electric power for households and commercial buildings; supplemental or auxiliary power to support car, truck and aircraft systems; power for personal, mass and commercial transportation; also the modular addition by utilities of new power generation closely tailored to meet growth in power consumption. These applications will be in a large number of industries worldwide. Fuel cell is an electrochemical device that converts chemical energy in fuels into electrical energy directly, promising power generation with high efficiency and low environmental impact. Because the intermediate steps of producing heat and mechanical work typical of most conventional power generation methods are avoided. Fuel cell is not limited by thermodynamic limitations of heat engines such as the Carnot efficiency. In addition, because combustion is avoided, fuel cells can produce power with minimal pollutant. However, unlike batteries the reductant and oxidant in fuel cell must be continuously replenished to allow continuous operation.

A fuel cell brings together hydrogen and oxygen with catalyst to produce electricity, waste heat and water. The single cell consists of electrolyte sandwiched between electrodes. The layout of fuel cell system was shown in figure 1.

In fuel cell system, bipolar/end plates are one of the most important and costliest components of the fuel cell stack and accounts to more than 80% of the total weight of the stack. These plates function as separator plates in between different cells, thereby keeping the oxidant and fuel from coming in direct contact. They support intricate gas flow-field channels that help to distribute the reactant gases uniformly over the reaction interface. These plates help to effectively remove reaction heat from the active area, thereby avoiding local buildup of heat. They also act as current collectors providing a series of electrical connections.

Figure 1. Layout of fuel cell system
connections in between individual cells and provide a basic infrastructure for the cell stack. The net efficiency of the fuel cell stack system depends on the performance of these plates in the fuel cell environment. The performance of these plates depends on the material and flow field design in the plates.

The conventional bipolar/end plate consists of machined flow field plate (flow channel). The conventional flow channel can be replaced by metal foam, because core materials such as open cellular metal foams possess good structural and conductive properties and can therefore replace the flow channel. The comparison of machined flow field plate with metal foam is shown in figure 2. Also the actual fabricated metal foam (SS 316) with 20 pores per inch (PPI) for flow field plate was shown in figure 3.

Figure 2. (a) Schematic of bipolar/end plate showing the machined channels; and (b) Schematic of bipolar/end plate with metal foam.

Figure 3. Fuel cell stack bipolar/end plate with metal foam as flow channel.
2. METHODOLOGY

The heat transfer required in the fuel cell system is determined by the thermodynamic principles of the chemical and electrochemical conversion in the system that converted hydrogen and oxygen into electricity, water and waste heat. The efficiency of a fuel cell is depending on the amount of power drawn from it. Higher power can result to higher current which increases the losses in fuel cell system. The higher power can also result to the lower efficiency. A typical cell running at 0.7 V has an efficiency of about 50%, meaning that 50% of the energy content of the hydrogen is converted into electrical energy; the remaining 50% will be converted into heat. (depend on the fuel cell system design).

The fuel cell system was divided into two reactants area, there are: hydrogen and oxygen area. The overall heat transfer coefficient is equivalent to the convection coefficient, because conduction and other thermal resistance can be neglected. In hydrogen area, the heat was transferred from the internal cell to the reactant (hydrogen) by forced convection. The heat also transferred by forced convection from hydrogen to the metal foam (SS 316). In oxygen area, the heat transfer phenomena are the same like in hydrogen area. The heat transfer scheme of fuel cell system was shown in figure 4.

In fuel cell system, hydraulics diameter (dh) can be calculated using formulae by substituting the area and circumference of bipolar plate. Reynold number (Re) was calculated to know the fluid flow type (laminar or turbulence) using formulae by substituting fluid physical properties, such as: density and dynamic viscosity, both in hydrogen oxygen reactant. Also the Reynold number in porous media can be calculated using formulae by replacing hydraulics diameter with permeability (K). In this paper,
the fluid velocity variation are: 2, 2.5, 3 m/s and permeability variation are: $10^{10}, 10^{11}$, and $10^{12}$.

\[
dh = \frac{4 \times A}{P} \quad (1)
\]

\[
Re = \frac{\rho \times v \times dh}{\mu} \quad (2)
\]

\[
Re = \frac{\rho \times v \times (K^{1/2})}{\mu} \quad (3)
\]

The Nusselt number (Nu) can be calculated using formulae 4 by substituting Reynold (Re) and Prandtl (Pr) number to those formulae. The coefficient of convection (hi) can be calculated using formulae 5 for heat transfer from the internal cell to the reactant and using formulae 6 for heat transfer from the reactant to the metal foam. The effective thermal conductivity for fluid in metal foam must be calculated first using formulae 7. Finally the convection heat (hi) can be calculated using formulae 8.

\[
Nu = 0.332 \times (Re^{1/2}) \times (Pr^{1/3}) \quad (4)
\]

\[
hi = \frac{Nu \times k}{dh} \quad (5)
\]

\[
hi = \frac{Nu \times k_{ef}}{dh} \quad (6)
\]

\[
k_{ef} = [(\varepsilon \times k_f) + ((1-\varepsilon) \times k_s)] \quad (7)
\]

\[
q = hi \times A \times (T_2 - T_1) \quad (8)
\]
3. RESULT AND DISCUSSION

Hydraulics diameter and Reynold number from the internal cell to the reactants, both in hydrogen and oxygen that have been calculated using formulae (1) and (2) was used velocity variation (2, 2.5, and 3 m/s). Also the Nusselt number, coefficient of convection and convection heat that have been calculated using formulae (3), (4), (5) must be substituted by hydrogen and oxygen physical properties, such as density, viscosity, Prandtl number and thermal conductivity. From the calculation, the results in hydrogen and oxygen reactant were shown in table 1.

**Table 1. Heat and fluid properties in hydrogen and oxygen reactant**

(heat transferred from the internal cell to the reactants)

<table>
<thead>
<tr>
<th>Properties</th>
<th>Hydrogen</th>
<th></th>
<th>Oxygen</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Velocity (m/s)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>2.5</td>
<td>3</td>
<td>2</td>
<td>2.5</td>
</tr>
<tr>
<td>Re</td>
<td>704.84</td>
<td>881.05</td>
<td>1057.26</td>
<td>4806.99</td>
<td>6008.74</td>
</tr>
<tr>
<td>Nu</td>
<td>7.815</td>
<td>8.373</td>
<td>9.571</td>
<td>20.458</td>
<td>22.872</td>
</tr>
<tr>
<td>hi (W/m² °C)</td>
<td>32.20</td>
<td>36.00</td>
<td>39.43</td>
<td>12.56</td>
<td>14.04</td>
</tr>
<tr>
<td>Q (W)</td>
<td>0.80</td>
<td>0.90</td>
<td>0.99</td>
<td>0.31</td>
<td>0.35</td>
</tr>
</tbody>
</table>

Based on the calculation result above, it can be concluded that Reynold number was increased with the increasing of velocity (formulae 2), because velocity has an affect in flow type (laminar/turbulence). Similar with Re number, the increase of velocity can make higher Nusselt number, coefficient of convection and heat of convection, because the increase of velocity can make heat transfer in the system happened faster.

The calculation of fluid flow and heat transfer phenomena (forced convection) in porous medium (metal foam) is the same like the calculation from the internal cell to the reactant (hydrogen or oxygen). The different is in Reynold number calculation. Re can be calculated using Reynold modified formulae (6) by replacing hydraulic diameter with permeability (K). Other different is in the calculation of convection coefficient; thermal conductivity must be calculated first using formulae (7). The result in hydrogen and oxygen for porous medium were shown in table 2.
Table 2. Heat and fluid properties in hydrogen and oxygen reactant
(heat transferred from the reactants to metal foam)

<table>
<thead>
<tr>
<th>Permeability</th>
<th>Properties</th>
<th>Hydrogen Velocity (m/s)</th>
<th>Oxygen Velocity (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>2.5</td>
</tr>
<tr>
<td>$10^{-10}$</td>
<td>Re</td>
<td>0.45</td>
<td>0.56</td>
</tr>
<tr>
<td></td>
<td>Nu</td>
<td>0.20</td>
<td>0.22</td>
</tr>
<tr>
<td></td>
<td>$h_i$ (W/m$^2$°C)</td>
<td>8.59</td>
<td>9.60</td>
</tr>
<tr>
<td></td>
<td>Q (W)</td>
<td>0.21</td>
<td>0.24</td>
</tr>
<tr>
<td>$10^{-11}$</td>
<td>Re</td>
<td>0.14</td>
<td>0.18</td>
</tr>
<tr>
<td></td>
<td>Nu</td>
<td>0.11</td>
<td>0.12</td>
</tr>
<tr>
<td></td>
<td>$h_i$ (W/m$^2$°C)</td>
<td>4.33</td>
<td>5.40</td>
</tr>
<tr>
<td></td>
<td>Q (W)</td>
<td>0.12</td>
<td>0.14</td>
</tr>
<tr>
<td>$10^{-12}$</td>
<td>Re</td>
<td>0.04</td>
<td>0.06</td>
</tr>
<tr>
<td></td>
<td>Nu</td>
<td>0.06</td>
<td>0.07</td>
</tr>
<tr>
<td></td>
<td>$h_i$ (W/m$^2$°C)</td>
<td>2.72</td>
<td>3.04</td>
</tr>
<tr>
<td></td>
<td>Q (W)</td>
<td>0.07</td>
<td>0.08</td>
</tr>
</tbody>
</table>

Based on the calculation of heat transfer phenomena from the reactant to the porous medium with velocity and permeability variation, it can be concluded that the increase of velocity can make higher Re number, because velocity has an affect in flow type. Also the decrease of permeability can reduce additional flow resistance in the system. Both velocity and permeability has an affect in heat transfer characteristic, because velocity can make the reactant (hydrogen and oxygen) to transfer heat faster and permeability related with pore and heat transfer surface area. The increase of permeability will result in the increase of Nusselt number, coefficient of convection and heat of convection in the system.

One of the most important properties in porous medium is permeability, because it has an effect on fluid flow and heat transfer in fuel cell system (as mention above). From figure 5 and 6, it can be concluded that the decrease of permeability resulting in decreasing of waste heat (total heat) and increasing of efficiency in fuel cell system, because in fuel cell, the power from the electrochemical reaction was transformed into electricity and waste heat, so if the waste heat increase; it will decrease the total efficiency in fuel cell system. The higher permeability can result to the increase of Reynold, Nusselt number and waste heat.
4. CONCLUSIONS

The metal foam can be used as a replacement for flow field plate (flow channel) in fuel cell bipolar plate, because it has less permeability ($10^{-12}$ m$^2$) compared to usual flow channel ($10^{-8}$ m$^2$). The decreasing of permeability can result in the decreasing of waste heat and the increasing of overall efficiency in fuel cell system.
REFERENCES