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Design of Forced Air-cooling Structure for Elevated Temperature PEMFC

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Abstract

Proper operating temperature range and homogenous temperature distribution are important to proton exchange membrane fuel cell (PEMFC). For the elevated temperature PEMFC water is not suitable to be used as coolant due to high operating temperature. Instead, air can be chosen as coolant because of the relative large temperature difference between fuel cell itself and the ambient air. In this paper, four types of forced air-cooling modes for elevated temperature PEMFC were discussed, and influences of other factors such as cooling air inlet velocity and thermal conductivity of bipolar plate material and fins on heat dissipation and temperature distribution were investigated. Three-dimensional computational fluid dynamics (CFD) method was employed to investigate fluid flow and heat transfer in the elevated temperature PEMFC on a 250 cm² single cell level. The temperature distribution fields on the active area of MEA were obtained and compared. One optimized mode, with suitable cooling air inlet velocity and bipolar plate material, was determined for future experimental study.

Keywords: Elevated temperature, PEMFC, Air-cooling, Cooling structure, CFD, Temperature distribution.

1. Introduction

As an energy convertor, proton exchange membrane fuel cell (PEMFC) has many advantages, including clean, efficient and high power density, etc., and it is regarded as an ideal power source for vehicles in the future[1,2].

Operating temperature is a critical factor for PEMFC since it greatly influences the performance and durability of the PEMFC. The ordinary operating temperature of a PEMFC is around 60- 80°C. Recent research has confirmed that PEMFC operated at an elevated temperature can bring many benefits, e.g. enhanced electrochemical kinetics for both electrode

reactions, simplified water management, and increased CO tolerance[3]. However, if the operating temperature is too high, it may lead to degradation on membranes, catalysts layers (CLs) and gas diffusion layers (GDLs). Since energy efficiency of fuel cell is approximately 50%, a kW-class PEMFC stack generates also the same amount of heat. Therefore, it is important to remove the excessive heat and keep PEMFC operating in a proper temperature range. Furthermore, a homogeneous temperature distribution in the active area is also very important for PEMFC. It can increase the kinetic rates at reaction sites and reduce the ohmic losses in the electrolyte [4]. At the same time the electrolyte mechanical strength can also be improved [5]. So a proper cooling structure must be designed to maintain

the internal temperature in a suitable range and achieve homogeneous distribution.

For PEMFC operating at elevated temperature, i.e. 90-95°C, water is no longer suitable to be chosen as coolant because the operating temperature is nearly reaching water's boiling point. Thermal oil and air were considered to be chosen as cooling mediums for elevated temperature PEMFC. Till now there are only limited literatures published on high temperature PEMFC stack [6-11], most of which chose thermal oil as coolant because of its higher boiling point and chemical stability at elevated temperature. However, the employment of thermal oil is also problematic. The leaking of thermal oil into the electrode will be lethal to the stack, and leaking to the outside environment will lead to pollution. Therefore the coolant loop should be properly separated from the bipolar plates. And then the stack structure became more complicated and the cost increased.

Due to the enlarged temperature discrepancy between PEMFC and the ambient air, air can be considered as an optional coolant. Instead of separated and complicated coolant circuit, simplified cooling system or structure can be used, e.g., cooling fins can be added by the bipolar border and then no pump is necessary and disadvantages of oil leakage can be avoided.

In the present work, three-dimensional computational fluid dynamics (CFD) method was employed to investigate fluid flow and heat transfer in the PEMFC on a single cell level. The temperature distributions in the active area by virtue of four types of air-cooling modes were obtained respectively, and then compared.

2. Mathematical modeling

2.1 Geometric model

The general (or typical) geometric model of the PEMFC is presented in Figure 1. As shown in Figure 2, the geometric model consists of GDLs, bipolar plate, fins, H₂/Air flow channels and cooling air flow channels. The fins are designed as elongated parts of the traditional bipolar plate. Cooling air flows over the fins and takes away the heat.

Figure 1 Typical geometric model of PEMFC

Nomenclature

p	: Relative pressure (Pa)
q	: Heat flux (W m^{-2})
t	: Time (s)
T	: Temperature (K)
$\vec{u}$	: Velocity vector (m s^{-1})

Greek letters

α	: Thermal diffusivity ($\text{m}^2 \text{s}^{-1}$)
ρ	: Density (kg m^{-3})
λ	: Thermal conductivity ($\text{W m}^{-1} \text{K}^{-1}$)
μ	: Viscosity ($\text{kg m}^{-1} \text{s}^{-1}$)

Subscripts

s	: Solid
f	: Fluid

Figure 2 Structure of the typical PEMFC geometric model

2.2 Assumptions

For modeling purposes, following assumptions were made:

- The operating condition is steady;
- All gases are treated as ideal gas;
- The incompressible air/H₂ are used as working fluid;
- Because of lower velocity of gases in flow channel, these zones are regarded as laminar zone;
- The thicknesses of the membrane and catalyst layer are ignored;
- The efficiency of the PEMFC is 50%;
- The heat source is located on the top surface of GDL, which doesn't contact with the bipolar plate, and it generates heat homogeneously;
- The GDL is porous.

2.3 Governing equations

The model in this contribution refers to fluid flow and heat transfer in a steady state, and the gravity influence

can be ignored.

For the fluid flow, the governing equations are described as follows:

Continuity equations

$$\nabla \cdot (\rho \vec{u}) = 0 \quad (1)$$

Momentum equation

$$\nabla \cdot (\rho \vec{u} \vec{u}) = \nabla \cdot (\mu \nabla \vec{u}) - \nabla p \quad (2)$$

In this model, heat transfer between the forced convection in gases flow and solid heat conduction in the bipolar plate, fins and GDLs are coupled. Therefore the equations for heat transfer in solid and fluid regions are constructed by balancing the energy in a control volume.

For the solid regions, i.e. bipolar plate, fins and GDLs, the governing equation of heat transfer is represented as:

$$\nabla^2 T_s = 0 \quad (3)$$

For the fluid regions, the governing equation of heat transfer is described as:

$$\frac{\partial T_f}{\partial t} + \vec{u} \cdot \nabla T_f = \alpha_f \nabla^2 T_f \quad (4)$$

The membrane and catalyst layer are considered as a homogeneous surface heat source, and the heat flow density is given by

$$q = \lambda \Delta T \quad (5)$$

2.4 Boundary conditions

This paper has investigated the influences on the cooling performance with different structures, different cooling air inlet velocities and different thermal conductivities of bipolar plate and fins.

In models, it is assumed continuity at all internal boundaries. The velocity and temperature of the feeding and cooling gases are given at the inlets. Within the active area a constant heat flux is given at the top surfaces of the both GDLs. The contact faces between the fluid domain and solid domain are coupled. All other out walls are assumed to be adiabatic.

The detailed geometry parameters are listed in Table 1.

Table 1 Parameters for numerical analysis

Item	Value
Electrical power of the fuel cell(W)	120
Heat generation of the fuel cell(W)	120
Active Area(cm ²)	250
Length of the bipolar plate(mm)	251
Width of the bipolar plate(mm)	163
Thickness of the bipolar plate(mm)	3.5
Thickness of the fins(mm)	1
Heat exchange area per fin(m ²)	1.956e-2
Cooling medium	Air
Heat flux per GDL top surface(W m ⁻²)	2400
Anode gas inlet mass flow (kg s ⁻¹)	2.9e-6
Anode gas inlet temperature(K)	368
Anode gas outlet pressure(Pa)	0
Cathode gas inlet mass flow(kg s ⁻¹)	1.97e-4
Cathode gas inlet temperature(K)	368
Cathode gas outlet pressure(Pa)	0
Cooling Air inlet velocity(m s ⁻¹)	10/20/30
Cooling Air inlet temperature(K)	298
GDL density(kg m ⁻³)	440
GDL thermal conductivity, through plane(W m ⁻¹ K ⁻¹)	1.7
GDL thermal conductivity, in plane(W m ⁻¹ K ⁻¹)	23
GDL specific heat(J kg ⁻¹ K ⁻¹)	840
Bipolar plate and fins density(kg m ⁻³)	1400
Bipolar plate and fins conductivity(W m ⁻¹ K ⁻¹)	20/50/100
Bipolar plate and fins specific heat(J kg ⁻¹ K ⁻¹)	935

2.5 Numerical procedure

In the simulation, a three-dimensional, single-phase, non-isothermal and heat transfer model is adopted and implemented into a commercial computational fluid dynamics (CFD) package, FLUENTTM, in order to investigate the temperature distribution on the active area of MEA. The solution procedure is based on SIMPLE algorithm with algebraic multigrid (AMG) method [12]. The solution is assumed to converge if the residuals for the velocity are all under 0.001 and the residual for energy is less than 0.000001.

3. Results and discussion

3.1 Cooling effect with different cooling modes

As shown in Figure 3, there are two types of structure, of which fins are constructed at either the longer or the shorter borders of the bipolar plates. According to the different cooling air inlet positions and flow routes, they can be divided into four cooling modes, i.e. mode A, mode B, mode C and mode D. The coolant flow rates and the heat exchange area of those four modes are all the same.

Figure3 Models of different cooling modes

In the simulations, the conductivity of bipolar plate and fins is $100 \text{ W m}^{-1}\text{K}^{-1}$, and the cooling flow velocity is 20 m s^{-1} . The temperature distributions on the active area under different cooling modes are shown in Figure 4.

It can be seen that the temperature distribution on the active area of mode C and D is more homogeneous than that of mode A and B. The table 2 shows that both of the average temperature and highest temperature of mode D is the lowest in the four modes. That means, with the same heat exchange area and coolant flow rate, the cooling effect of mode D is better than the others.

Figure 4 Temperature distributions on the active area under mode A, B, C, D, respectively

Table 2 Indexes of temperature distribution with different cooling modes

Cooling mode	Average temperature (K)	Highest temperature (K)	Standard deviation of temperature distribution(K)
Mode A	431.2	445.7	12.5
Mode B	385.0	395.2	11.2
Mode C	382.7	393.8	10.5
Mode D	366.8	381.7	10.3

3.2 Cooling effect with different cooling flow velocities

The cooling air flow velocity is an important parameter for the cooling system design, which can determine the type and the power of the cooling fan. Table 3 lists the cooling effect at different cooling air inlet velocities under mode C. The results illustrate that the temperature declines with the cooling flow velocity increasing.

Table 3 Indexes of temperature distribution with different cooling flow velocities

Flow velocity (m s^{-1})	Average temperature(K)	Highest temperature(K)
10	399.9	415.5
20	382.7	393.8
30	373.9	388.5

3.3 Cooling effect with different thermal conductivities

Traditionally, the most widely used materials for bipolar plate are the graphite/polymer composites, which are ideal in terms of corrosion resistance and conductivity [13, 14]. Because of high mechanical strength and easily forming, metal such as aluminum, stainless steel becomes a new option as the bipolar plate materials [15]. Due to different properties of these materials, the thermal conductivity varies widely. The temperature distribution's indexes with different thermal conductivities under mode C are presented in table 4. It shows that the cooling effect improves with the increasing of the bipolar and fins thermal conductivity, and the temperature decreases obviously and the temperature distribution becomes more homogeneous.

Table 4 Indexes of temperature distribution with different thermal conductivities

Thermal conductivity (W m ⁻¹ K ⁻¹)	Average temperature (K)	Highest temperature (K)	Standard deviation of temperature distribution (K)
20	500.4	562.5	43.6
50	418.1	445.4	19.2
100	382.7	393.8	10.5

4. Conclusions

Three-dimensional fluid flow and heat transfer analysis of an elevated temperature PEMFC cooling structure was carried out using CFD software FLUENT™. The cooling performance of different cooling modes, different cooling air inlet velocities and different thermal conductivities were obtained and compared.

For air cooling design, mode D is the best choice, by which excessive heat can be removed more effectively than others. Furthermore, increasing the cooling air inlet flow rate and the thermal conductivity of the bipolar plate and fins can improve the cooling performance and achieve more homogeneous temperature distribution.

The experimental results of these fluid flow and heat transfer in the elevated temperature PEMFC models are not readily available to compare the simulation results. In the next step, experimental works will be done with purpose of validation test of the modeling and simulation results. As an important measure, thermocouples will be employed to verify the temperature distribution inside the cell.

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