Waste Heat Recovery Technology Based on Thermoelectric Couple for Fuel Cell

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Abstract

In recent years, due to global warming and carbon emissions increase, many countries focus on the development of green energy, and waste heat recovery technology is also noticed. Hydrogen is a new energy that is clean, efficient and sustainability, wherein fuel cells attract attention that can transform energy from hydrogen to electricity directly without exhausting gas but heat. In this paper, thermoelectric couple is used to recover the waste heat from fuel cell into electricity power to provide vehicle required or other devices. The simulation result shows that thermoelectric couple can efficiently deal with above work. In addition, an intelligent controller will be designed to improve the output stability of renewable system.

Keywords: Thermoelectric Couple, Proton Exchange Membrane Fuel Cell, Waste Heat Recovery.

1. Introduction

In recent years, due to the petrochemical energy shortage, global warming, and the Carbon emissions increase, many countries focus on the development of green energy, and the system efficiency and recoverability are also noticed. Hydrogen is a new energy that is clean, efficient and sustainability, so it soon gets the international attention.

Fuel cells are the most promising energy technology, the principle is the reverse reaction of electrolyzed water, injects hydrogen and oxygen into the anode and cathode plate, and it generates power, water and heat. Its applications include transportation and power plants.

The Seebeck Effect was first discovered in metal in 1821. It's foundation of thermoelectric effect⁽¹⁾. When a thermoelectric couple has temperature difference across two

side, it will generate voltage. When input voltage to it, it will generate temperature difference.

In the past studies, they recover waste heat based on thermoelectric couples (TEC) for proton exchange membranes fuel cells (PEMFC), but the number of the TEC was less, so the voltage generated was lower. It cannot be used effectively in other device. Therefore, we think that we can increase the number of TEC to generate more voltage. It can be used to the battery charging or the motor operation.

In this study, we use MATLAB/SIMULINK to build a model of PEMFC and TEC to simulate the waste heat recovery of fuel cell, and use thermoelectric couple to transform the waste heat to electric power.

2. Matlab Mathematical Model

2.1 Worldwide Harmonized Light Vehicles Test Procedure

We use Worldwide Harmonized Light Vehicles Test Procedure (WLTP) to simulate the real road conditions, WLTP is a globally unified driving cycle measurement standard, it sets some driving conditions to measure the speed of the vehicle as shown in Fig. 1.

Fig. 1. WLTP

However, the unit of WLTP is speed, so I have to transform the unit to power (W), the unit transform can use the Eq. 1. In this equation, P is the power required of the vehicle, M is the mass of the vehicle, g is gravitational acceleration 9.81m/s^2 , f_r is the rolling resistance coefficient of the tire, ρ_a is air density 1.202kg/m^3 , C_D is air resistance coefficient of the vehicle, A_f is the front half area of the vehicle, V is speed of the vehicle and the unit is m/s .

$$P_v = (M \times g \times f_r + \frac{1}{2} \rho_a C_D A_f V^2 + M \frac{dV}{dt}) \times V \quad (1)$$

2.2 PEM Fuel Cell Model

(A) Electrical model

When a cell provides power to the load, the no-load voltage (V_n), is reduced by three classes of voltage drop, the activation (V_{act}), ohmic (V_{ohm}), and concentration (V_{conc}).

There is a polarization curve which is generally used to express the feature of a FC as shown in Fig. 2.

Fig. 2. Polarization curve.

In general, the voltage of the FC could be found using Eq. 1.

$$V_{cell} = V_n - V_{act} - V_{ohm} - V_{conc} \quad (1)$$

(a) Nernst voltage

The Nernst equation can calculate the total voltage of the cell, the equation is as Eq. 2. The V_0 ideal voltage is 1.229 V.

$$V_n = V_0 + \frac{RT}{2F} \ln(P_{H_2} \times (P_{O_2})^{\frac{1}{2}}) \quad (2)$$

R is universal gas constant, T is stack temperature the unit is $^{\circ}\text{K}$, F is Faraday constant, P_{H_2} is pressure of hydrogen, P_{O_2} is pressure of oxygen.

(b) Activation polarization

Activation polarization can be analyzed by Tafel's equation, if the current density is larger, the electrode potential is more deviated from the equilibrium, so the required voltage is larger⁽²⁾.

$$V_{act} = \frac{RT}{\alpha n F} \ln \frac{i}{i_0} \quad (3)$$

α is the constant between 0-1 that is the electron transfer coefficient of hydrogen and oxygen in the reaction, n is the number of electrons released during the reaction, i is the cell current density, i_0 is the current density released during the hydrogen ion and oxygen ion reaction.

(c) Ohmic polarization

Ohmic polarization is the consumption effect when ions, charged defects, electron holes or electrons are transported within the electrolyte or the electrode.

$$V_{ohm} = A I R_r \quad (4)$$

A is reaction area, I is current density, R_r is the total resistance of the cell.

(d) Concentration polarization

At high current densities, reactants transport to the reaction sites slowly is the main reason for the concentration polarization⁽³⁾.

$$V_{con} = \frac{RT}{nF} \ln(1 - \frac{i}{i_L}) \quad (5)$$

i_L is the limiting current density.

(B) Thermal model

In a FC, only a little of the internal energy in the hydrogen can be converted into electricity, the remaining energy is either dissipated or absorbed by the FC, it causes the FC operating temperature increase⁽⁴⁾. Based on the thermal energy balance applied to the FC, the equation is:

$$Q_n = Q_g - Q_e \quad (6)$$

Q_n is system's internal heating power acquired, Q_g is heating power generated, Q_e is heating power dissipated.

The FC heat generation is due to the heating power released by the chemical reaction (Q_c), the electrical power generated by the FC (P_s) and the heating power associated with the sensible and latent heat (Q_{se+la}) of the reactants and the reaction product⁽⁴⁾. Q_g is represented by the following equation:

$$Q_g = Q_c - P_s - Q_{se+la} \quad (7)$$

Q_c is the quantity of energy entering the system per time unit. It depends on the enthalpy potential of the FC and the electron transfer rate in the reaction⁽⁴⁾. So, the equation is:

$$Q_c = \frac{\Delta h_{f,H_2O,1}^0}{zF} N_s i_s \quad (8)$$

$\Delta h_{f,H_2O,1}^0$ is the enthalpy of liquid water formation (285.84 kJ mol⁻¹ at 25 °C and 1 bar), N_s is number of series cells, i_s is current of the FC.

P_s is power of the FC, it obtained through voltage (V_{FC}) and the FC stack current, the equation is:

$$P_s = V_{FC} i_s \quad (9)$$

Q_{se} is sensible heat that is defined as heat received by a substance and which cause the temperature increased without affecting its state⁽⁴⁾.

Q_{la} is latent heat that is defined as the energy required for a substance to change phase⁽⁴⁾.

$$Q_{se+la} = m_{H_2} c_{p,H_2} (T - T_a) + m_{O_2} c_{p,O_2} (T - T_a) + m_{H_2O} H_{v,H_2O} \quad (10)$$

m_{H_2} is the mass flow rate of hydrogen, m_{O_2} is the mass flow rate of oxygen, m_{H_2O} is the mass flow rate of water, c_p is specific heat, H_v is enthalpy of vaporization, T is FC operating temperature, T_a is ambient temperature.

Q_e is heating power dissipated that is defined as the product between the heat transfer coefficient (H_t) and the temperature difference between T and T_a ⁽⁴⁾. The equation is:

$$Q_e = H_t (T - T_a) \quad (11)$$

2.3 Thermoelectric Couple Model

Thermoelectric couple is a device that can generate electric power by using temperature difference⁽¹⁾, it is based on Seebeck Effect. The Seebeck Effect was first discovered in metal in 1821⁽¹⁾, Thomas Johann Seebeck found when the two different metals compose a closed loop and the temperature on the junction is different, the compass pointer is deflected. Therefore, he thought the temperature difference caused the metal to produce a magnetic field, but he did not discover the current in the closed loop, so he called the phenomenon “thermomagnetic effect”. Danish physicist Hans Christian Ørsted rectified the oversight and coined the term “Thermoelectric Effect”. Thermoelectric couple (TEC) is a kind of semiconductor material⁽⁵⁾, composed by many thermoelectric wafers as shown in Fig. 3.

Fig. 3. A typical configuration of TEC⁽⁶⁾.

In Fig. 3, hot side temperature of module is T_h , cold side temperature of module is T_c , and we can calculate the temperature difference (D_t) by Eq. 12.

$$D_t = T_h - T_c \quad (12)$$

q_h is output heat from module, it can be obtained as

$$q_h = (S_M I T_h) + K_M D_t - \frac{I^2 R_M}{2} \quad (13)$$

q_c is input heat to module, it can be obtained as

$$q_c = (S_M I T_c) + K_M D_t + \frac{I^2 R_M}{2} \quad (14)$$

In Eq. 13 and 14, S_M is Seebeck coefficients, I is output current from module, K_M is the thermal conductance of module, R_M is resistance of module.

The voltage generated by the Seebeck Effect can be obtained as

$$V_{out} = D_t \times S_M \quad (15)$$

In Eq. 13-15, Seebeck coefficients and thermal conductance are different in every metal materials, so the parameters of Seebeck coefficients and thermal conductance must be changed in different metal materials.

2.4 Cooling Plate

PEMFC have high power density while operating at relatively low temperatures (about 80°C)⁽⁷⁾. Therefore, heat dissipation of PEMFC is very important, if the temperature is too high, polymer membrane inside will burn⁽⁷⁾.

This is traditional cooling plate as shown in Fig. 4.

Fig. 4. Traditional cooling plate⁽⁷⁾.

In the simulation, we embed the TEC in the cooling plate as shown in Fig. 5, and the TEC absorb heat of PEMFC and then dissipate heat through the cooling plate.

Fig. 5. TEC embed in cooling plate.

The temperature of solid region of the cooling plate is T_s , and we can calculate T_s by Eq. 16.

$$T_s = \frac{q}{h} + T_w \quad (16)$$

q is heat flux, h is heat transfer coefficient, T_w is water temperature⁽⁷⁾.

3. Result

In the simulation, we use Eq. 1 to calculate the power required of the vehicle in drivecycle of WLTP. The result is two cycles show in Fig. 6. This is the input of PEMFC.

Fig. 6. Power for PEMFC.

After calculating the power required, put it into PEMFC model, and then we can get the operation temperature of PEMFC shown in Fig. 7.

Fig. 7. Temperature of PEMFC.

This value is the most important of all. After calculating the temperature, we put it into TEC model to generate the voltage. Assume that the water temperature is constant at 25 °C, D_t can be calculated by Eq. 12 shown in Fig. 8.

Fig. 8. Temperature difference (D_t).

The voltage of each TEC can be calculated by Eq. 15 shown in Fig. 9.

Fig. 9. Voltage of TEC.

4. Discussion

The optimum operating temperature of PEMFC is about 333 K to 335 K. The simulation results of Fig. 9 indicate that, about 0.9 V of voltage can be generated in about 333 K. Therefore, assume that there 65 PEMFC stacks are used and stuck with 64 TECs to recycle the waste heat energy, and connect TECs in series, the total voltage is about 58 V. However, the more number of TECs increased, the higher voltage can be generated. The power generated by TECs can be used to charge the battery, if PEMFC cannot provide power to the motor suddenly, TECs can provide power urgently until PEMFC is operating normally.

5. Conclusions

After the simulation, we verify that the temperature is larger, the voltage generated by TEC is larger. In the result, when the PEMFC operating temperature is about 333 K to 335 K, and the total voltage generated by TECs is about 58 V, the more number of TECs increased, the higher voltage can be generated. However, Seebeck coefficients and thermal conductance are different in every metal materials, so select the most suitable materials to achieve the best efficiency is very important. The operation temperature of PEMFC is about 80 °C to 100 °C, there is no waste heat recovery system can recover the waste heat in this range in general. So it is the most outstanding characteristic of TEC. In future work, we will find the number of TECs and the best configuration in series or in parallel. There is an intelligent controller will be designed to improve the output stability of renewable system.

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