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Analysis performance of proton exchange membrane fuel cell (PEMFC)

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Abstract. Recently, the proton exchange membrane fuel cell (PEMFC) has gained much attention to the technology of renewable energy due to its mechanically ideal and zero emission power source. PEMFC performance reflects from the surroundings such as temperature and pressure. This paper presents an analysis of the performance of the PEMFC by developing the mathematical thermodynamic modelling using Matlab/Simulink. Apart from that, the differential equation of the thermodynamic model of the PEMFC is used to explain the contribution of heat to the performance of the output voltage of the PEMFC. On the other hand, the partial pressure equation of the hydrogen is included in the PEMFC mathematical modeling to study the PEMFC voltage behaviour related to the input variable input hydrogen pressure. The efficiency of the model is 33.8% which calculated by applying the energy conversion device equations on the thermal efficiency. PEMFC's voltage output performance is increased by increasing the hydrogen input pressure and temperature.

1. Introduction

Due to the awareness of the environmental issues, many of the researcher explores for clean energy source technology to replace the conventional energy [1]. In that case, hydrogen is found as one of the alternative sustainable renewable energy source for future [1][3][4]. Regarding to the electrical energy consumption, a system named fuel cell is introduced as a zero-pollutant electrical energy source. The fuel cell uses hydrogen gas and oxygen taken from the surrounding to produce electricity by the chemical reaction that is oxidation reduction. The process of a fuel cell is similar to the process of electrolysis where the usage of two electrodes to separate the electron to produce electricity and water as a result at the anode.

The reaction will also produce heat from the separation of electron in the oxygen atom where the separation of the electron will need a certain amount of heat to successfully remove the electron from the atom and combine with the hydrogen to produces water [5]. The PEM fuel cell is a fuel cell that used hydrogen as an electrolyte and a fast emerging in the green technology to replace the current renewable energy sources problems. The current renewable energy sources are too dependent on the surroundings and didn't produce much energy that will fulfil the requirements of a certain process. The needs in controlling the pollution of using fuel that releasing carbon monoxide that are polluting the air massively.

The research for fuel cell research and applications has been increasing rapidly from the last ten years and reached over 1.5 billion USD in the year 2007 where the fuel cell has been successfully applied on the areas that requires independent power supplies and a primary energy sources. In Malaysia, numbers of economic corridors planned in the future and for the present growth energy consumption where the needs for an independent power supplies would be a heavy demand especially when the development today are more on alternative energy resources [6]. Hydrogen could be an important energy carrier in the future where an energy carrier moves and delivers energy in a useable form towards the consumers. Producing energy using hydrogen which is can be stored and transport to other locations when needed will results in a high demand for hydrogen in the future technology.

The technology can be applied to the industrial production by changing the current machinery supplies and also opens up new market of a renewable energy which leads towards more job opportunity and more experts in the future. The PEM fuel cell can operate up to 200°C temperature and normally operates at 80°C and this was caused by the electric current productions where the higher amount of power produced will lead to a higher amount of heat [7]. Compared with the other types of fuel cells, a proton exchange membrane fuel cell (PEMFC) shows promising results with its advantages such as low temperature, high power density, fast response, and zero emission if it is run with pure hydrogen, and it is suitable for use in portable power supply, vehicles, and residential and distributed power plants [8][9][10].

The difficulties in obtaining an accurate PEMFC dynamic model is getting the parameters of the model to be used in modelling model [11]. The parameters can affect the voltage, power, temperature characteristics of the simulated stack. The parameters value used are primarily based on experiments and manufacturing data. There are some aspects on the operation of PEMFC are still hard to accurately model and some processes are property of the manufacturers. The importance of the physical and electrochemical processes occurs in a fuel cell can be evaluated using a generalized multi-parametric sensitivity analysis (MPSA) which includes the entire model parameter space [12].

The Figure 1 shows the electrical model for PEMFC illustrates the losses of the fuel cell by using resistor and capacitor that important consideration to include in the modelling. The application of the charge double layer capacitance (CDL) where it is a phenomenon of a jumping charge between two contacted surfaces as in this case it is a reaction in the electrode and the electrolyte by connecting capacitor parallel to Rconc and Ract. Ract is known as the cathode and the Rconc known as anode of the fuel cell operation. The open circuit voltage (OCV) is the value of cell voltage exact to an operation under 100°C. The OCV is expressed in Gibbs free energy release, $\Delta\bar{g}f$. The equation of the gibbs free energy released can be expressed in equation (1).

$$E = \frac{-\Delta\bar{g}f}{2F} \tag{1}$$

The purpose of this paper is to analyze the performance of Proton exchange membrane (PEMFC) by using a thermodynamic model. The developing of the mathematical thermodynamic model is by using Matlab/Simulink simulation software. This paper will also discuss the contribution of heat from the differential equation used to develop the thermodynamic mathematical model and the effects on the amount of heat and pressure produced towards the output voltage of the PEMFC.

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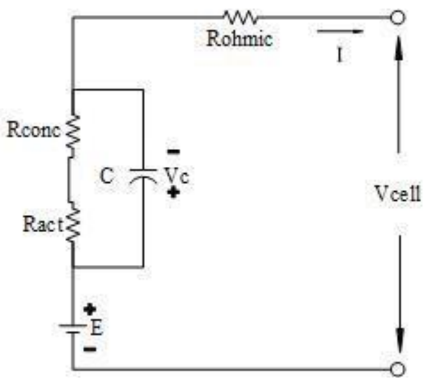

Figure 1. Electrical model for PEMFC.

2. Model specification

This section describes the simulation model for PEMFC. The modeling is using a few mathematical equations [13] and the parameter specifications of Horizon H-500 Fuel Cell System [14] in order to simulate the model as a real-time fuel cell stack system. Firstly, the mathematical modeling of the PEMFC is built in Matlab/Simulink environment using steady-state and thermodynamic model. The area of the cell is important requirement needed to simulate the PEMFC mathematical modelling due to its potential to produce much potential in a wider area cell. Besides, other than the physical characteristics, thermal and pressure behavior are also considered in the simulation. The current demand from the load are used as the input parameter for the simulation PEMFC mathematical model which can expect the power needed for the usage.

Modelling of the fuel cell considered the steady state requirements first before proceeding to the thermodynamic. In the steady-state consideration, there are four conditions that needed to be considered which is an area of cell, temperature of cell, input pressure and the current demand based on the Horizon- 500 parameter. The input pressure of the fuel cell is coming from two types of gases which are hydrogen gas and oxygen gas. The input pressure for hydrogen is set to a certain value which represents the hydrogen gas from a tank while for the oxygen gas is taken from the surrounding of the system.

$$E = 1.229 - 8.5\times10^{-4}(T_{cell} - 298.15) + 4.308\times10^{-5}(\ln PH_2 + \tfrac{1}{2}PO_2) \quad (2)$$

$$P_{H2} = 0.5PH_2O^{sat}[\exp\left(-\frac{4.192J}{T_{cell}{}^{1.334}}\right)\frac{P_a}{PH_2O^{sat}} - 1] \quad (3)$$

$$PO_2 = PH_2O^{sat}[\exp\left(-\frac{4.192J}{T_{cell}{}^{1.334}}\right)\frac{P_a}{PH_2O^{sat}} - 1] \quad (4)$$

$$\log_{10} PH_2O^{sat} = -2.18 + 2.95\times10^{-2}T_c - 9.18\times10^{-5}T_c^2 + 1.44\times10^{-7}T_c^3 \quad (5)$$

In the mathematical model of PEM fuel cell the partial pressure of these two gases gives effect to the ideal equilibrium potential, E as shown in equation (2). Both partial pressure of hydrogen and oxygen can be obtained by using the equation (3) and (4). Pa in equation (3) is the partial pressure for anode while J is the current density (A/cm^2). Besides, Pc in equation (4) is the partial pressure for cathode and P_{H2Osat} is the saturation pressure for water. The hydrogen and oxygen pressure from the surroundings are important in order to get the partial pressure of the hydrogen and partial pressure of the oxygen in the PEM fuel cell.

Thermodynamic is also important to include in the modelling. It is a coupled of a complex system which is the flow of fluid-solid-heat and electrochemistry where it is considered as the process of the electrochemical reaction. In addition, it is the operation for both membrane level and the auxiliary systems [13][15]. In dynamic, there is charge double layer capacitance (CDL) and the open circuit voltage. Charge double layer capacitance is the factor that causing the behavior of the fuel cell where CDL is the jumping or transfer of charge between to metal plate contacted. In the system, CDL occurs between the cathode and the anode and the potential of CDL labelled as V_c can be expressed as in equation (6).

$$V_c = V_{acto} + V_{conc} \tag{6}$$

In equation (6), the V_{conc} is the results for the change of the concentration of the reactants as they consumed in the reaction and the V_{acto} were taken from the steady-state model. The output of the dynamic is the cell voltage and the cell power where taken from the open circuit voltage (OCV) where OCV is the value of an open circuit voltage exacted to an operation of the fuel cell under 100°C. The output cell voltage can be expressed in equation (7) where E is the reversible voltage, V_{conc} is the concentration voltage, V_{act} is the activation voltage and V_{ohmic} is the ohmic voltage.

$$V_{cell} = E - V_{conc} - V_{act} - V_{ohmic} \tag{7}$$

The most common way of expressing the efficiency of the fuel cell is based on the change in standard free energy for the cell reaction which can be expressed in equation (8) where the reaction produced water in form of liquid [16]. The thermal efficiency on energy conversion is defined as the amount of useful energy produced towards the change in chemical energy stored that is released when a fuel cell reacts with an oxidant (oxygen). The ideal thermal efficiency of fuel cell on pure hydrogen and oxygen at standard condition is 0.83 where the actual efficiency of the fuel cell can be expressed in terms of the ratio of the operating cell voltage to the ideal cell voltage as in equation (9). The ideal voltage of a fuel cell is reversibly with pure hydrogen and oxygen in standard condition is 1.229V. Therefore, an actual fuel cell thermal efficiency of the operation at a voltage of V_{cell}, based on greater value of heating hydrogen is expressed as in equation (10).

$$\eta_e = \frac{\Delta G}{\Delta H} \tag{8}$$

$$\eta_e = \frac{0.83 V_{cell}}{V_{ideal}} \tag{9}$$

$$\eta_e = \frac{0.83 V_{cell}}{1.229} \tag{10}$$

A fuel cell may operate in different values of current densities where corresponds of the cell voltage then determines the fuel cell efficiency. A decrease in current density is resulting in an increase in cell voltage and thus increase the efficiency of the fuel cell. It can be described as the current density decreased the active cell area must be increased in order to obtain the desired amount of power.

3. Results and discussion

In this section, the results obtained from the PEMFC modelling are shown and discussed. The model is simulated by using a real-time specification from Horizon H-500 Fuel Cell Systems. Thirty six of cells are used and the area of cells is taken from the dimension stated in the data sheet which is 250mm x 190mm x 75mm are inserted into the simulation. Besides that, the value of pressure and temperature is set manually in order to observe the performance of the fuel cell system depending on that two physical quantities. The maximum temperature of the system is set to 338.15K.

3.1. Performance effects

At standard condition, 293.15K of temperature and 1.00 atm, gas pressure is used in the model [17]. The standard value of temperature is used as the input temperature for the model while the standard value of gas pressure is used at the cathode side which represent input oxygen pressure that obtained from the air the surroundings. Besides, the input pressure of hydrogen gas is set to 1.45 atm in the modelling. This section briefly explains the thermodynamic voltage and power output performance in a single cell. The stack performance of the PEMFC can be obtained from [13].

Figure 2 illustrates the single cell voltage performance for PEMFC versus current density. The single cell voltage is obtained from equation (7). Current density is the current demand per area of the cell in a PEMFC system. The voltage starts at 1.229V then decline rapidly at first due to the activation reaction in the PEMFC, then it's slowly decrease in the middle of time due to the ohmic losses. Finally, the voltage concentrates at 0.3V. Besides, Figure 3 shows the output power deliver in each cell of the PEMFC system. The power is increased by increasing current demand on the system until at one time the power is rapidly dropping before it reaches in a steady state condition due to the dryness of the cell [18][19][20]. Thus, the performance of the PEMFC is depending on the characteristics of the membrane and its limitation [21][22][23].

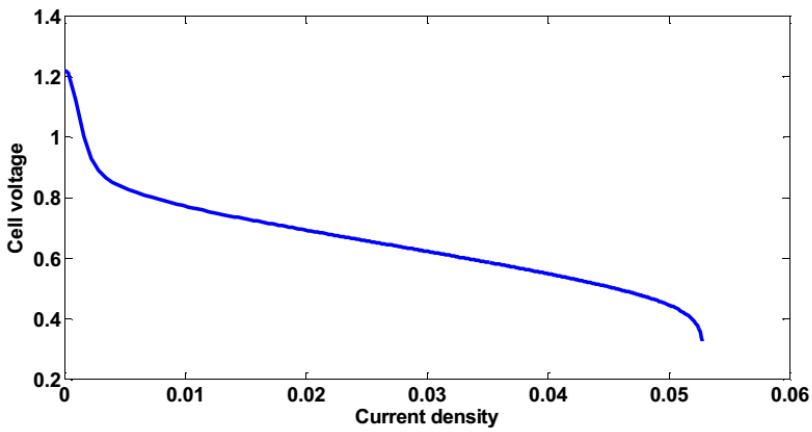

Figure 2. Single cell voltage performance.

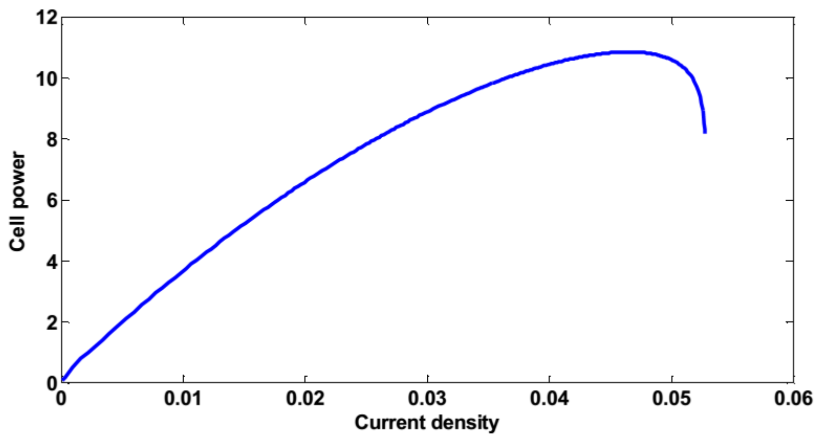

Figure 3. Single cell power performance.

For thermodynamic behavior, equation (6) as discussed in section 2 will affect in the voltage performance. Figure 4 illustrates that the variation of the temperature makes sense of the performance of the fuel cell voltage output in a single cell at a certain duration of current demand. The temperature of the system is varied from 293.15K to 313.15K. As the results, 293.15K of temperature has the lowest of output voltage performance compared to 298.15K, 303.15K, 308.15K and 313.15K. Therefore, from the figure below, it clearly shows that the higher the temperature of the system, the higher the voltage deliver from the PEMFC.

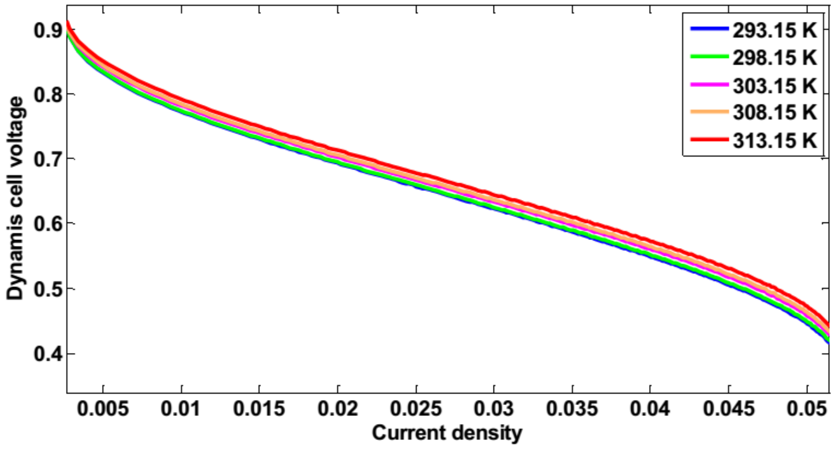

Figure 4. Performance on a single cell of the PEMFC depends on temperature effect.

On the other hand, input pressure also gives affects towards the performance of the PEMFC as stated in equation (2). Input hydrogen pressure and input oxygen pressure are two types of pressure included in the PEMFC model. In this paper, the input hydrogen pressure is varying from 1.00 atm until 1.60 atm while the input oxygen pressure is remaining the same as 1.00 atm which represents as air standard pressure. Figure 5 shows that the output voltage performance in a single cell is slightly different with the variation of the pressure. In the range of 1.00 atm to 1.60 atm, the higher level of the input pressure gives the higher output voltage [24]. However, it might be a large difference in a higher pressure level and in stack performance.

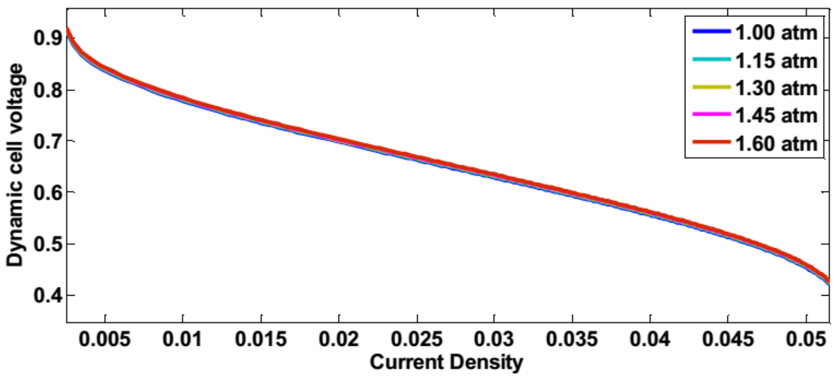

Figure 5. Performance on a single cell of the PEMFC depends on pressure effect.

3.2 Model efficiency
Figure 6 explained that the ideal and the actual voltage deliver from a single cell of the PEMFC is slightly different. The ideal voltage is mean that the voltage of PEMFC which is before the cell considers all the internal losses of the system which is represented in the actual voltage. The efficiency for the modelling of the PEMFC is calculated by using equation (10)**.** Thus, from the formula, the efficiency of the PEMFC modelling is 33.8%. It is 15.5% percent difference with the Horizon H-500 series FC system which deliver 40% efficiency [14].

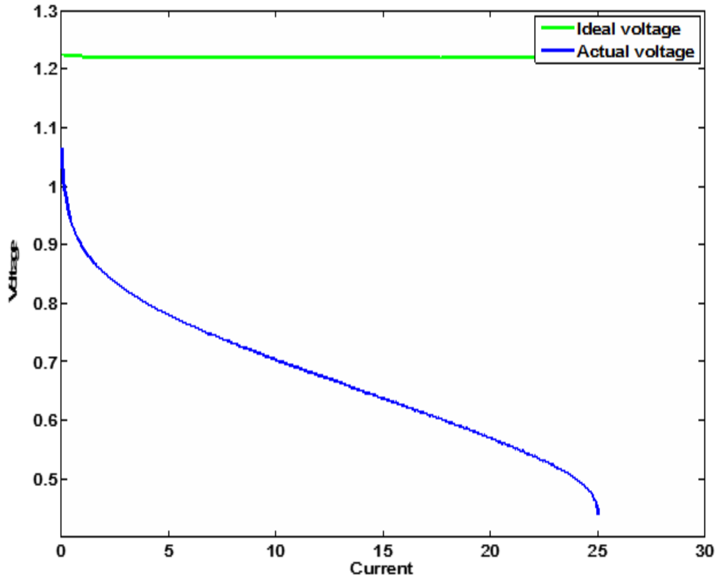

Figure 6. Ideal and actual voltage on a single cell of PEMFC.

4. Conclusion
As a conclusion, the output performance of the PEMFC is affected by varying the two parameters in this paper which are temperature and pressure. The higher the temperature and pressure inserted into the system, the better the performance. However, the over supplied input pressure and temperature will damage the membrane of the PEMFC. For further research, the limitation of the input supply and other parameters should consider in the model.

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