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Fuel Consumption Model of Electric Vehicle Fed by PEM Fuel Cell

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Abstract : *This paper presented the modeling and simulation of fuel consumption of electric vehicle fed by PEM Fuel Cell. The proposed system consists of the PEM Fuel Cell, the model that used to determine the electric energy consumption for driving vehicle and model that used to calculate the fuel consumption. The models developed in this paper used the Neural Netwrk models for the PEM Fuel Cell. The purpose of this study was used to determine hydrogen consumption and to predict driving range and used to determine heat and water as a product of PEM fuel cell. Simulation was done using the vehicle speed as the input. Using the electric energy consumption model, the required power of the electric motor can be obtained. The Neural Network model of the PEM fuel cell was used to predict the stack current and voltage of the PEM fuel cell. The stack current was used to calculate the fuel consumption and to predict the driving range of electric vehicle. The simulation results showed that every electric vehicle traveled a distance of 100km needed the hydrogen of 0.9575kg and the predicted range of 368.5km are obtained if used a tank of 3.92kg hydrogen. The estimated range was compared with published manufacturer specifications.*

Keywords *- PEM fuel cell, electric vehicle, neural network (NN) model, fuel consumption*

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I. INTRODUCTION

Electric vehicles are being developed as a solution to reduce an oil consumption and reduce gas emissions that produced by the internal combustion engines[1]. Electric vehicle uses batteries as an electric energy source to operate the vehicle. The disadvantages of the battery-powered vehicle are the weight of the vehicle and the long recharging time[2].

The fuel cell vehicles are expected to be able to overcome the disadvantages of battery-powered vehicle. A fuel cell is a source of electrical energy using hydrogen and oxygen to generate electricity. The fuel cell produces only the heat and the water therefore the fuel cell vehicle will reduce an automotive air pollution. Polymer Electrolyte Membrane Fuel Cell (PEM Fuel Cell) is suitable used in vehicles as an electric power source[3]. Electricity can be generated continuously by a fuel cell as long as hydrogen, is continuously supplied. Hydrogen can be stored in a storage tank. By using a high-pressurized hydrogen tank, so that the fuel cell can drive the vehicle for a long time[4]. Fuel consumption and driving range are primary factors to be considered in the operation of electrical vehicles. They are necessary to determine the compressed hydrogen tank size.

The fuel consumption model for the electric vehicle is used to estimate the fuel consumption of the electrical vehicle. The model parameters can be input into the proposed model and using the vehicle speed to generate the electric energy consumption. The neural network model of PEM fuel cell is used to predict the stack voltage[5]. The hydrogen consumption and driving range can be predicted via simulation before constructing the electric vehicle.

II. MODEL DEVELOPMENT

The proposed model presented in this paper is shown in fig.1. The models are the electric energy consumption model, the Neural Network (NN) model of PEM Fuel Cell and the fuel consumption model. The model of electric energy consumption is used to obtain the required power of the electric motor. The output of this model can be input into the NN model of PEM Fuel Cell. The stack current of the PEM Fuel Cell is used to calculate the fuel consumption. From these models also can be used to analyze the driving range of the electrical vehicle and to calculate the heat and water as the product of PEM Fuel Cell.

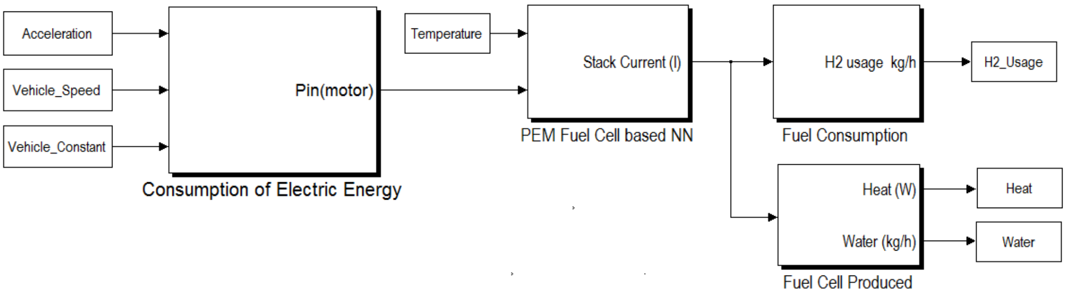

Fig.1. The proposed model

2.1 Model of Electric Energy Consumption

This model is used to determine the power required for electric vehicle. The inputs are vehicle speed and acceleration , and the output is the mechanic power (P_m). The power P_m in W, is given by[6],

$$P_m = (C_{rr}.m.g + 0.5\, C_d.\, \rho.A_f.\, v^2 + m.g.\sin\psi + m.a)\, v \qquad (1)$$

where m is the weight of the vehicle, kg; g is the gravitational acceleration, m/s^2; C_{rr} is the coefficient of wheel friction, dimensionless; C_d is the coefficient of form, dimensionless; ρ is air density, kg/m^3; A_f is shape of the surface of the vehicle, m^2; v is the vehicle speed, m/s; ψ is the slope of road; a is the acceleration, m/s^2;

The required power (P_{in}) of electric motor is equal total power that should be transferred to the wheels (P_m) divided by the efficiency of the motor (η).

$$P_{in} = \frac{P_m}{\eta} \qquad (2)$$

2.2 Neural Network Model of PEM Fuel Cell

The PEM fuel cell voltage (V_{stack}) is affected by the current (I) and temperature (T) stack. The relationships between V_{stack}, I and T are mapped by the neural network (NN). This model has been developed using feed-forward neural network with the back propagation (BP) algorithm. The NN model has been successfully trained to predict the stack voltage[5]. The structure of the NN model is shown in fig.2. The NN model of the PEM fuel cell consists of the input layer, the hidden layer and the output layer. The inputs of the network are the electric current of motor and temperature of the fuel cell, and the output is the stack voltage. A specific activation function used in the hidden layers is a sigmoid bipolar and in the output layer is an identity.

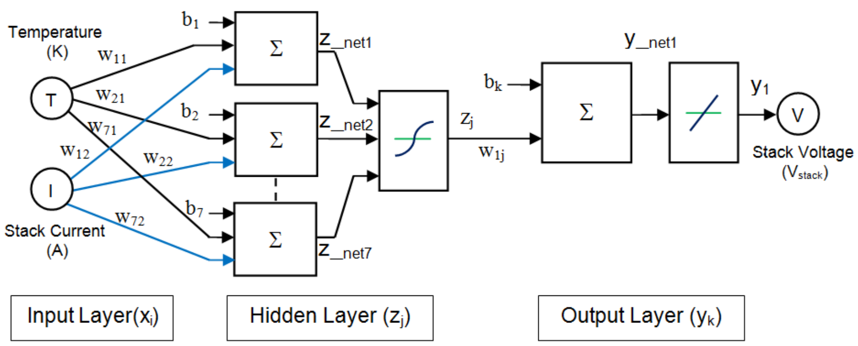

Fig.2. Neural network structure for prediction of the stack voltage [7]

The relationship between the input layer and the output layer gives the formula as follows [7]. The output in the hidden layer:

$$z\_net_j = b_{j0} + \sum_{i=1}^{n} x_i v_{ji}$$

$$z_j = \text{tansig}(z\_net_j) = \frac{2}{1 + e^{-z\_net_j}} - 1 \qquad (3)$$

The output in the output layer is given by

$$y\_net_k = b_{k0} + \sum_{j=1}^{p} z_j w_{1j}$$

$$y_k = V_{stack} = purelin(y\_net_k) = y\_net_k \quad (4)$$

The NN model can be used to estimate the stack voltage of the PEM fuel cell. The stack voltage of PEM Fuel Cell is used to obtain the electric current of the motor. The required stack current of electric motor is equal total power (P_{in}) divided by the stack voltage of motor.

2.3 Fuel Consumption

The hydrogen mass flow of the fuel cell stack is a linear function of the current drawn from the fuel cell and number of cell of the fuel cell stack. The formula is given by [8]:

$$\dot{m}_{H2} = \frac{I \cdot n}{2 \cdot F} \text{ mol/s} \quad (5)$$

$$\dot{m}_{H2} = \frac{I \cdot n}{2 \cdot 96487} = 5{,}18 \cdot 10^{-6} \cdot I \cdot n \text{ mol/s} \quad (6)$$

where $\dot{m}_{H2}$ is hydrogen mass flows (mol/s), I is stack current (A), n is number of cell , F is Faraday constant (96487 C/mol). The molar mass of hydrogen is 2.02×10^{-3} kg/mol, so this becomes

$$\dot{m}_{H2} = 5.18 \cdot 10^{-6} \cdot 2.02 \cdot I \cdot n \text{ kg/s} = 1.05 \cdot 10^{-5} \text{ I.n kg/s}$$

$$\dot{m}_{H2} = 1.05 \cdot 10^{-5} \cdot n \frac{P_{stack}}{V_{stack}} \text{ kg/s} \quad (7)$$

The oxygen consumption depends on the current drawn from the fuel cell and the number of cells. The oxygen mass flow of the fuel cell stack can be calculated using the following equition[8].

$$\dot{m}_{O_2} = \frac{I \cdot n}{4 \cdot F} \text{ mol/s} \quad (8)$$

The molar mass of oxygen is $32 \cdot 10^{-3}$ kg/mol, so equition (8) becomes

$$\dot{m}_{O_2} = \frac{32 \cdot 10^{-3} I \cdot n}{4 \cdot 96487} \text{ kg/s} = 8{,}29 \cdot 10^{-8} \cdot I \cdot n \text{ kg/s} \quad (9)$$

However, the oxygen used will normally be derived from air, so we need to adapt equation (9) to air usage. The molar proportion of air that is oxygen is 0.21, and the molar mass of air is 28.97×10^{-3} kg/mol. So, equation (9) becomes

$$\dot{m}_{air} = \frac{28{,}97 \cdot 10^{-3} I \cdot n}{0{,}21 \cdot 4 \cdot 96487} \text{ kg/s} = 3{,}57 \cdot 10^{-7} \cdot I \cdot n \text{ kg/s} \quad (10)$$

In practice the air flow is well above stoichiometry, typically twice as much. Stoichiometry is the ratio between air flow in provided by the compressor and air consumed in the reaction. If the stoichiometry is λ, then the equation for air consumption (10) becomes:

$$\dot{m}_{air} = 3{,}57 \cdot 10^{-7} \cdot \lambda \cdot I \cdot n \text{ kg/s} \quad (11)$$

where $\dot{m}_{air}$ is air mass flows (kg/s), I is stack current (A), n is number of cell.

2.4 Fuel Cell Produced

a. Water Production

Produced water of the PEM fuel cell is modeled by [8] :

$$\dot{m}_{H_2O} = \frac{I \cdot n}{2 \cdot F} \text{ mol/s} \quad (12)$$

The molar mass of water is $18{,}02 \cdot 10^{-3}$ kg/mol, equation (12) becomes :

$$\dot{m}_{H_2O} = \frac{18{,}02 \cdot 10^{-3} I \cdot n}{2 \cdot 96487} \text{ kg/s} = 9{,}34 \cdot 10^{-8} \cdot I \cdot n \text{ kg/s} \quad (13)$$

Every hour the fuel cell produces water :

$$\dot{m}_{H_2O} = 9{,}34 \cdot 10^{-8} \cdot I \cdot n \cdot 3600 = 0{,}33624 \cdot 10^{-3} \cdot I \cdot n \text{ kg} \quad (14)$$

where $\dot{m}_{H2O}$ is water mass flows (kg/s), I is stack current (A), n is number of cell.

b. Heat Produced

Heat is produced when a fuel cell operates. The heat generated for a stack of n cells at current I, is as follow [8] :

$$H = n \cdot I \cdot (E_{max} - V_{out}) \text{ W} \quad (15)$$

where H is heat produced of fuel cell (W), E_{max} is maximum cell voltage of fuel cell that is 1,48V (HHV) or 1,25V (LHV), V_{out} is cell voltage of fuel cell (V), I is fuel cell current (A), n is number of cell of fuel cell.

2.5 Driving Range And Time

Driving range of the electric vehicle is obtained by amount of hydrogen in the hydrogen tank, that is :

$$\text{driving range (km)} = \text{vehicle speed}\left(\frac{\text{km}}{\text{h}}\right) * \text{driving time (h)} \quad (16)$$

$$\text{driving time (h)} = \frac{\text{amount of hydrogen (kg)}}{\text{hydrogen consumption}\left({}^{\text{kg}}/{}_{\text{h}}\right)} \quad (17)$$

III. RESEARCH METHODE

The parameters of the electric vehicle to simulate the proposed system are reported in table 1. The ECE 15 drive cycle is used as input data to calculate fuel consumption and driving range. The ECE-15 drive cycle is shown in fig.3 and parameters of this cycle can be seen in table 2. The ECE-15 cycle has a maximum speed of 50km/h, an average speed of 23.87km/h, a duration of 195s, and a length of 0.994km.

"**Table 1** Electric Vehicle Parameters"

Component	Parameter
Vehicle	Total vehicle mass : 1200 kg, Wheel friction coefficient C_{rr} : 0.013, Shape of the surface of the vehicle (A_f) : 1.8 m^2, Coefficient of form (C_d) : 0.23, Air density (ρ) : 1.25 kg/m^3 , Gravity(g): 9.81 m/s^2 , Gear Ratio (G): 7, Radius of wheel (r) = 0.3 m.
PEM Fuel Cell	E_o = 2 x 65V , P = 2 x 6kW.
Hydrogen Tank	171 L (3.92kg), 35MPa (350bar)

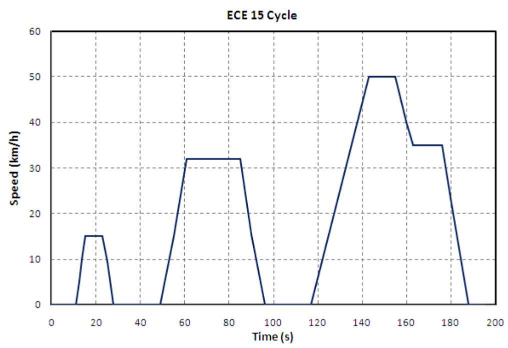

Fig.3 ECE 15 Cycle [9]

"**Table 2** Parameter of ECE 15 Cycle [9]"

Total distance	994 m
Total time	195 s
Driving time	150 s
Average driving speed	23.87 km/h
Maximum speed	50 km/h
Average positive acceleration	0.348 m/s^2
Average negative acceleration	- 0.393 m/s^2

The procedure that used to simulate this system is as follows:

a. Use given value of the vehicle speed calculates the electric energy consumption of the electrical vehicle using equations (1 and 2).
b. Using the electric energy of the electrical vehicle predicts the stack PEM fuel cell voltage using the algorithm of the neural network model.
c. Calculate the fuel consumption using equations (7 and 11).
d. Calculate the fuel cell produced using equations (14 and 15).
e. Calculate the driving range using equations (16 and 17).

IV. DISCUSSION AND RESULT

The vehicle speed is entered into the electric energy consumption model. Simulation is done with speed of ECE 15 cycle as input. The resulted power is used to determine the voltage and current stack of the fuel cell. Fig.4. show the stack voltage and current of PEM fuel cell during ECE 15 drive cycle. The stack current rises and the stack voltage of fuel cell drops when accelerating.

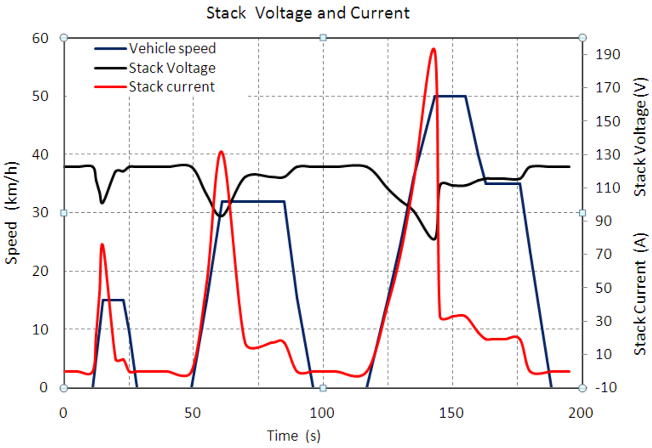

Fig.4. Stack voltage and current during ECE 15 cycle

Fuel consumption of a given vehicle depends on the stack current. To determine fuel consumption uses equation (7). Using ECE 15 drive cycle hydrogen consumption can be calculated. Fig.5, 6, and 7 are hydrogen consumption during ECE 15 cycle. Fig. 5 shows instant hydrogen consumption and total hydrogen consumption during ECE 15 cycle. Fig.6 shows that hydrogen consumption depends on distance with varying speed. At high speeds the vehicle requires more hydrogen consumption than low speed.

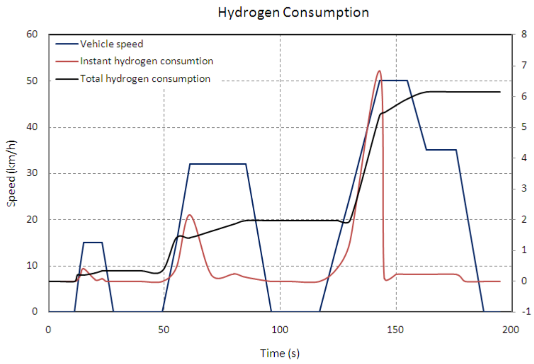

Fig.5. H_2 consumption during ECE 15 cycle

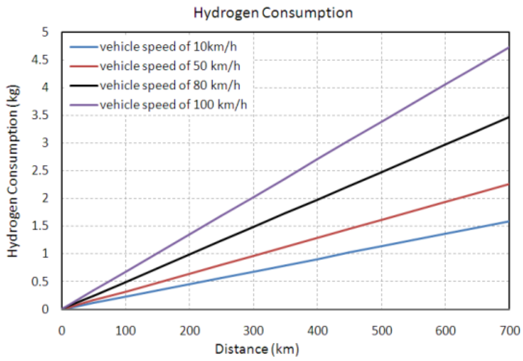

Fig.6. H_2 consumption vs. distance

Air and H_2 consumption at varying constant speed is shown in fig 7. At an average speed of 50km/h, the electric vehicle consumes hydrogen of 0.1613 kg/h or 0.3226kg/100km and air of 21.94 kg/h or 43.88kg/100km. So if a vehicle travels a distance of 500 km with an average speed of 50km/h and requires a tank with hydrogen mass of 1.613 kg (see fig.6).

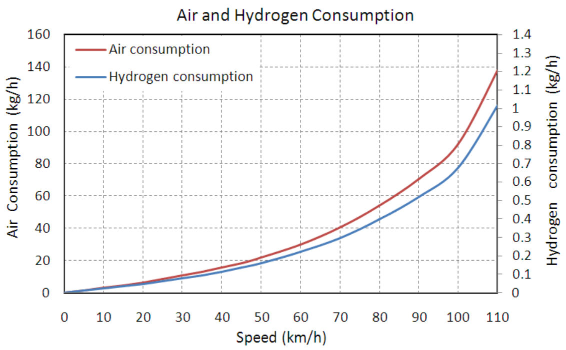

Fig.7. Air and H_2 consumption vs. constant speed

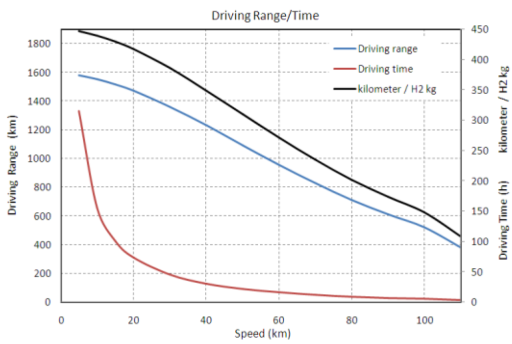

Fig.8. Driving range and driving time

Driving range and time can be obtained using equations (16-17). Driving range and time that can be reached by electric vehicle are determined by the amount of fuel (hydrogen) in the storage tank. Fig. 8 show driving range and time at a constant speed and hydrogen of 3.92kg in a tank. At a constant speed of 40km/h a electric vehicle can travel about a distance of 1200km.

A vehicle with hydrogen of 3.92 kg in the tank is simulated in ECE 15 cycle. About 90% of fuel tank is used to supply PEM fuel cell. Results of simulations are presented in table 3.

"**Table 3.** Simulation results of electric vehicle during ECE-15 cycle"

Driving range	368.5 km
Driving time	15.44 hour
Hydrogen consumption	0.2286kg/h
Air consumption	31.08kg/h
Heat production	2546W
Water production	2.033kg/h
Stack voltage	107.8V
Stack current	46.51A

The driving range of the simulation is compared with published manufacturer specifications. Table 4 show the published range information by the manufacturer.

"**Table 4.** Driving range of fuel cell vehicles [10]"

Model	FCX Clarity	2005 FCX	Adv. Focus FC 2002	Proposed Model
Vehicle weight	1625 kg	1670 kg	-	1200kg
Maximum speed	160 km/h	150 km/h	-	100km/h
Range	450 km	430km	290km	368.5km
Fuel cell stack	PEM Fuel Cell 100kW	PEM Fuel Cell	PEM Fuel Cell 85kW	PEM Fuel Cell
Hydrogen pressure	35 MPa(5000psi)	34.4 MPa	5,000 psi	350bar
Hydrogen storage volume	3.92kg	3.75kg	4kg	3.92kg

V. CONCLUSION

The proposed system has been presented in this paper. The main models for calculating fuel consumption and range of electric vehicle are model vehicle, fuel cell model and storage tank model. PEM Fuel Cell as a source of energy in electric vehicle is modeled by a neural network. Using the mathematical software can be done to simulate the fuel consumption model. The results of simulation showed that an estimated hydrogen consumption of 0.9575kg/100km and a range of 368.5km are obtained for ECE-15 cycle if 90% of fuel tank is used. The result of the simulation is compared with published manufacturer specifications for driving range.

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