Journal of Traffic and Transportation Engineering 6 (2018) 164-175
doi: 10.17265/2328-2142/2018.04.002

Theoretical Propulsion System for Fuel Cell Vehicles with Infinite Cruising Range

Katsutoshi Ono

Department of Energy Science & Technology, Kyoto University, Kyoto 606-8501, Japan

Abstract: The realization of a clean automobile society would require electrically-powered propulsion systems in vehicles. In recent years, electric vehicles have attracted considerable attention from the perspective of utilizing electricity generated from natural sources, such as solar and wind power. The propulsion method considered in the present investigation differs from the conventional off-board energy scheme in a manner such that pure stoichiometric H_2/O_2 fuels for fuel cells are generated on-board during vehicle operation. In this method, energy conversion occurs by means of ESI-PSE (electrostatic-induction potential-superposed electrolysis). If a quasi-static process is assumed, the theoretical power requirement to produce pure stoichiometric H_2/O_2 fuels is only 17% of the total energy required owing to a new method for supplying power to the EC (electrolytic cell). If an ESI-PSE EC is combined with a fuel cell (FC) to form an energy cycle, a HREG (hydrogen redox electric power generator) that uses solid PEMs (polymer electrolyte membranes) for the EC as well as the FC can be realized. According to calculations based on data from the operational conditions of commercially available ECs and FCs, more than 70% of the power delivered from the FC can be extracted for driving a motor constantly while a car is in motion. Because of energy self-sustainability on the HREG side, the power control system should not have any power loss. This propulsion system will realize tough vehicles that can continue running at a top speed at long unlimited cruising range.

Key words: Fuel cell vehicle, infinite cruising range, water electrolysis, electrostatic energy, electrostatic induction.

Nomenclature

A	Electrode surface area
ΔE	Extra-applied voltage
E_d^o	Theoretical decomposition voltage
E_d	Practical decomposition voltage
E_e	Electrolytic voltage
E_{FC}	FC single cell voltage
E_{EC}	EC single cell voltage
E_{FC}^o	Theoretical voltage of FC single cell
E_{EC}^o	Theoretical voltage of EC single cell
I_e	Electrolytic current
I_{FC}	Current flowing through the FC stack
I_{EC}	Current flowing through the EC stack
J_{FC}	Current density of the FC cell
J_{EC}	Current density of the EC cell
M_{net}	Net hydrogen output rate from a generator
M_r	Recycling rate of hydrogen from an ESI-PSE stack to a fuel cell stack
M_{FC}^o	Weight of an existing FC stack
M_{EC}	Weight of a single EC stack in the HREG system
$M_{FC}^{(r)}$	Weight of a set of the FC cells responsible for producing the power returned
M_T	Gross weight of the HREG system
N_{FC}	Number of FC cells connected in series in the FC stack
N_{FC}^o	Number of FC cells connected in series in the existing FC stack
N_{EC}	Number of EC cells connected in series in the EC stack
$N_{FC}^{(r)}$	Number of FC cells generating the power returned from FC stack to EC stack
P	Power requirement for a single voltage source electrolytic scheme
$P*$	Power requirement for ESI-PSE mode
P_T^o	Maximum power output from an existing FC stack
P_T	Maximum power output from an FC stack in the HREG system
P_r	Power returned from the FC stack to the EC stack
P	Partial pressure of gaseous species
$P_{M(max)}$	Maximum power provided by FC stack
R_M	Resistance of motor
V_{FC}	FC stack voltage
V_M	Voltage applied to motor
Α	Non-dimensional factor
Θ	Voltage efficiency of FC
ξ	Cycle power efficiency

1. Introduction

A conventional EV (electric vehicle) is powered by electricity from off-vehicle energy sources. To realize an EV with infinite cruising range, electrical energy for driving the electric motor must be generated on-board without using any external energy source when a car is running. In the present work, we describe a specific propulsion system for EVs called a HREG (hydrogen redox electric power generator) [1-4]. This generator is based on a combined energy cycle composed of FCs (fuel cells) that produce power and an ESI-PSE (electrostatic-induction potential-superposed water electrolytic cells) for synthesizing a stoichiometric H_2/O_2 fuel for the FCs. ESI-PSE is realized by using an alternative electrical circuit connected to the ECs (electrolytic cells). The HREG offers considerable advantages. Firstly, this device can function with zero energy and zero material inputs, and zero emission, without violating the laws of thermodynamics. The $H_2O \rightarrow H_2 + 1/2 O_2$ reduction reaction proceeds in the ESI-PSE, which functions on the "zero power input" mechanism that involves electrostatic-to-chemical energy conversion. This unit uses power equal to 17% of total energy that is theoretically required, while the remaining 83% can be provided by electrostatic energy free of power. A part of the power delivered by the FC is returned to the ESI-PSE cell, while the remainder represents the net power output available to drive the electric motor. In addition to cycling the generated power, H_2O, which contains heat from the exothermic reaction in the fuel cell, is transferred to the electrolytic cell to be utilized for the endothermic reduction reaction. The entire propulsion system may be equipped with commercially available technologies; and there is no need for other advanced technologies. It is suggested that full power should be extracted from the FC into the PCS (power control system) constantly. A part of this power can be used to drive the motor, and the remainder is wasted. Because there is no power loss in the HREG, the wasted energy does not translate into energy loss. Research on vehicles with infinite cruising range vehicle is nascent, and the underlying method was outlined in a previous paper [5]. The present paper is an extended version that is useful for making engineering judgement about this propulsion system.

2. Principle of ESI-PSE

We found that based on electrostatic-induction and the potential superposition theorem of dc circuits, an electrical circuit can reflect the *V-I* characteristic curve for water-electrolysis shown in Fig. 1. This curve implies that the total cell voltage is the superposition of two separate voltages: (1) the practical decomposition voltage, E_d and (2) the additional applied voltage ΔE, which when superposed on E_d, yields the electrolytic current, I_e, and the ionic current, I_{ion}, in the electrolyte solution. ΔE is then identified as the electromotive force (*emf*) for the electrolytic current, I_e.

Because the decomposition voltage E_d is a limit to the null-current static condition, it is identified with the barrier potential [6-9]. For a cell undergoing electrolysis, the voltage source external to the cell must supply a voltage E_e, given by

$$E_e = E_d + \Delta E \quad (1)$$

When the current I_e flows, by the application of E_e, the product $E_e I_e$ represents the total power that the power supply is required to provide. The value of this power is dependent on the value of E_d, as expressed by:

$$P = I_e (E_d + \Delta E) \quad (2)$$

The first term $E_d I_e$ represents the power provided by the source to the electrons to overcome the barrier potential E_d before the cell conducts. This extra power is required exclusively for typical SSE (single-voltage source electrolysis), but does not contribute directly to the electrolytic reactions. The current I_e flows due to the *emf* of ΔE, not $E_d + \Delta E$, so that the second term $I_e \Delta E$ is the electrical power that is useful specifically for the electrolytic reactions at the electrode/solution interface. Thus, the electrical energy required by typical standard single voltage source electrolysis is the total power.

Corresponding author: Katsutoshi Ono, professor, research field: energy science.

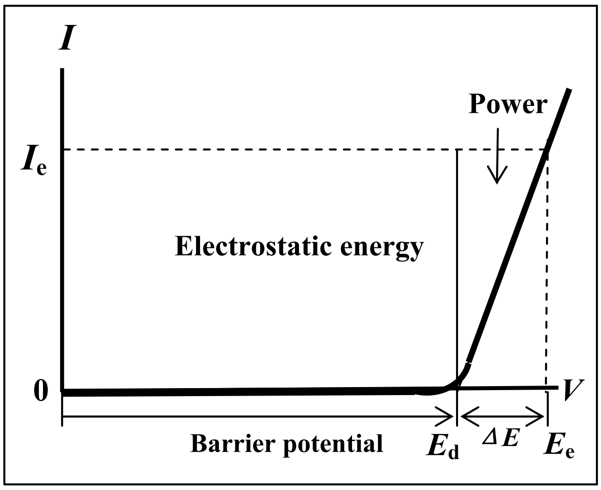

Fig. 1 Voltage-current characteristics of water electrolysis.

The method of ESI-PSE supplies potentials to the electrodes in a dual mode. That is the superposition of voltages using two independent voltage sources; a bias-voltage-source, which induces E_d at the cell electrodes, and a dc power supply, which provides power to the cell. These sources can act in parallel independently, and supply the electrodes with individual potentials, thus yielding a superposition such that the resulting voltage between the cell electrodes equals the magnitude of the algebraic sum of the individual potential, i.e., $E_d + \Delta E$. The bias-voltage source does not need to produce current, but merely a static voltage because of the null current condition at E_d. If the current of I_e flows to produce pure stoichiometric H_2/O_2 fuel for fuel cell, the power provided by the power supply and consumed in the cell (the total power requirement of the ESI-PSE) can be written in the simple form independent of E_d,

$$P^* = I_e \Delta E \quad (3)$$

Eqs. (2) and (3) have been verified by direct measurements of the power requirements of each cell (Fig. 2) [4]. Fig. 3 shows the basic construction of the ESI-PSE water-EC stack. The electrode potential of any individual cell in the stack is driven by electrostatic induction. The outermost pair of electrodes acts as a field generator, and these electrodes are connected to power supply, PS1, while the electrodes next to the field generator electrodes are connected to power supply PS2. There is no need for lead wires to carry the current from each inner cell. PS1 is employed to induce a potential, E_d, in (n-1) series cells, and the total potential between the first and nth electrodes is (n-1)E_d. When a voltage of (n-1)(E_d+ΔE) is applied between these electrodes using PS2, with a polarity opposite to that induced by PS1 (i.e., (n-1)E_d), an *emf*ΔE appears at each cell owing to potential superposition. Thus, current, I_e, flows through the electrolytic circuit owing to the total *emf*, which is equal to (n-1)ΔE. Therefore, the power requirements of the external power circuits are given by,

$$P^* = I_e(\text{n-1})\, \Delta E \quad (4)$$

for the ESI-PSE mode, and

$$P = I_e(\text{n-1})\, (E_d + \Delta E) \quad (5)$$

for the conventional (SSE) mode. The ESI-PSE can be applied to other electrochemical cells that exhibit a *V-I* curve of the form shown in Fig. 1.

3. On-board HREG system

3.1 Construction of the On-board HREG System

The major components of an on-board HREG system comprise a FC stack, an ESI-PSE cell stack (or EC stack) and a rechargeable battery for providing the power to start a car and to power car accessories. The battery is recharged on-board using the power delivered

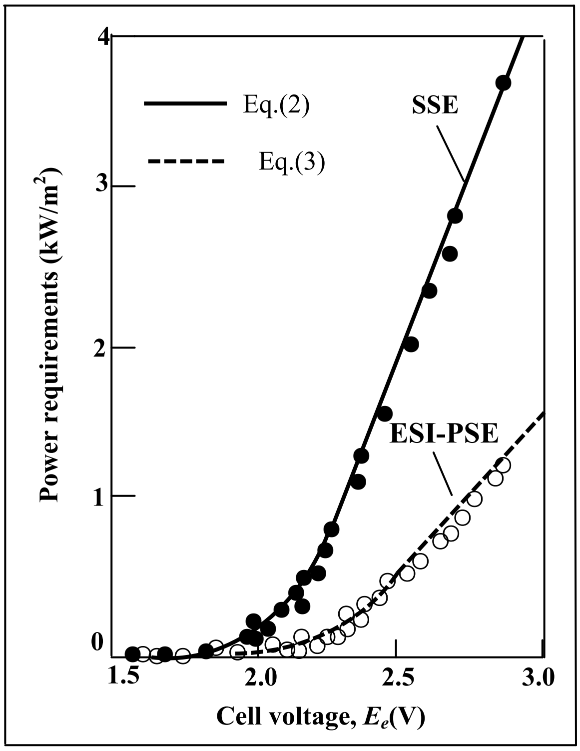

Fig. 2 Comparison of the measured power requirements with theory. Electrolyte: H_2O-10%NaOH; Temperature: 300 K.

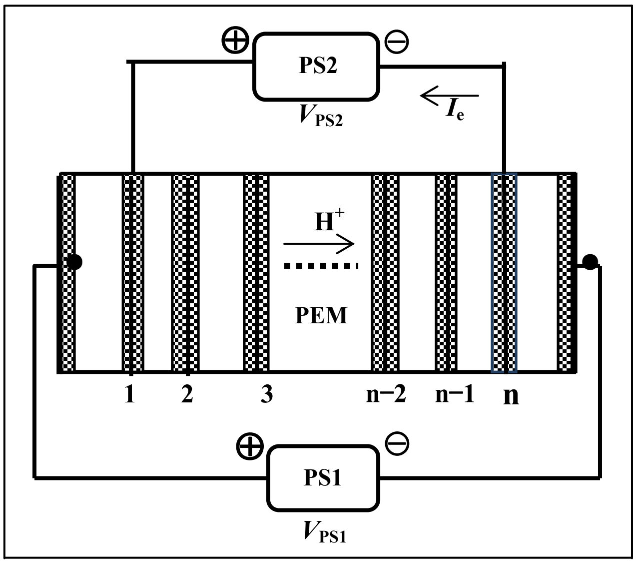

Fig. 3 Series connected EC stack in ESI-PSE mode. n: number of cell electrodes; FG: field generator.

by the FC stack and is used to assist the propulsion system. A standard HREG system configuration is shown in Fig. 4. The FC stack converts the H_2/O_2 fuel provided by the EC stack into electricity, which powers the vehicle's electric motor. The HREG is a closed energy cycle, in which a part of the power, P_r, generated by the FC stack is returned to the EC stack and the remainder represents the net power output. In addition to cycling the generated power, the heat from the exothermic reaction in the FC stack held by H_2O is

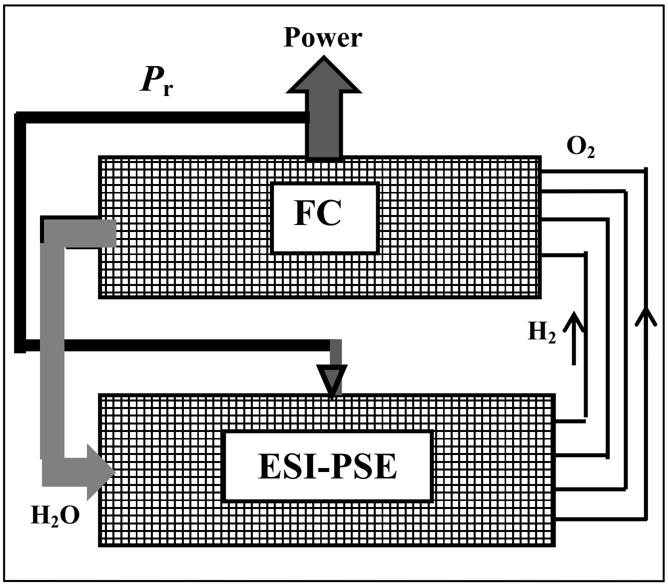

Fig. 4 On-board HREG system. P_r: power returned from FC to ESI-PSE.

transferred to the EC stack to be used in the endothermic reaction in this stack. Because fuel for the FC stack is generated continuously while the vehicle is in motion, the driving range can essentially be considered unlimited.

Fig. 5 shows a simplified diagram of the on-board HREG propulsion system. The PEM (polymer electrolyte membrane) FC stack is employed in commercial fuel cell vehicles [10]. Moreover, the same PEM cell stack is used for the water EC stack without major modifications; the only change is made to the power supply circuit external to the electrolytic cell.

A solid PEM is used for both the FC and the ESI-PSE water EC. The cell electrodes comprise a current collector, gas diffusion electrode and catalyzer electrode. Because these components are electrically conductive, the field generators can induce potentials in the inner electrodes. Notably, the structure of the PEM EC cell must be identical to that of a typical PEM FC cell. A conventional FCV uses an assembly of 370 cells in a FC stack to generate 400 V [11].

The PEM HREG system is a closed gas transfer system in which H_2, O_2, H_2O and heat circulate in a steady state (Fig. 5a). The FCs are connected to the ECs with the shortest possible distance. A steady state gas stream always exists in the channels between the cells owing to the pressure gradient from the ECs to FCs.

3.2 Operational Conditions

To design a compact HREG system, the output density of the overall unit should preferably be as high as possible Therefore, the overall power balance of the two-stage electric power generation system must be considered. In general, the output voltage of a FC, E_{FC}, is somewhat lower than the theoretical open-circuit voltage, E_{FC}^{o}, owing to the polarization effect. If voltage loss (i.e., voltage efficiency) is $\theta = E_{FC} / E_{FC}^{o}$, the power delivered by the FC is given by:

$$P_{FC} = I_e \theta E_{FC}^{o} \quad (6)$$

The mass balance in the power cycle requires the electrolytic and galvanic currents to be equivalent. The current efficiency of the EC is close to unity. Therefore, subtracting Eq. (3) from Eq. (6) yields the theoretical net power extracted from the generator, P_{net}. As an index of energy efficiency, we can define the integrated cycle power efficiency, ξ, as the ratio of the power extracted from the generator to that produced by the H_2/O_2 FC as follows:

$$\xi = P_{net}/P_f = 1-\Delta E/\theta E_{FC}^{o} \quad (7)$$

It is evident that as ΔE decreases the cycle power

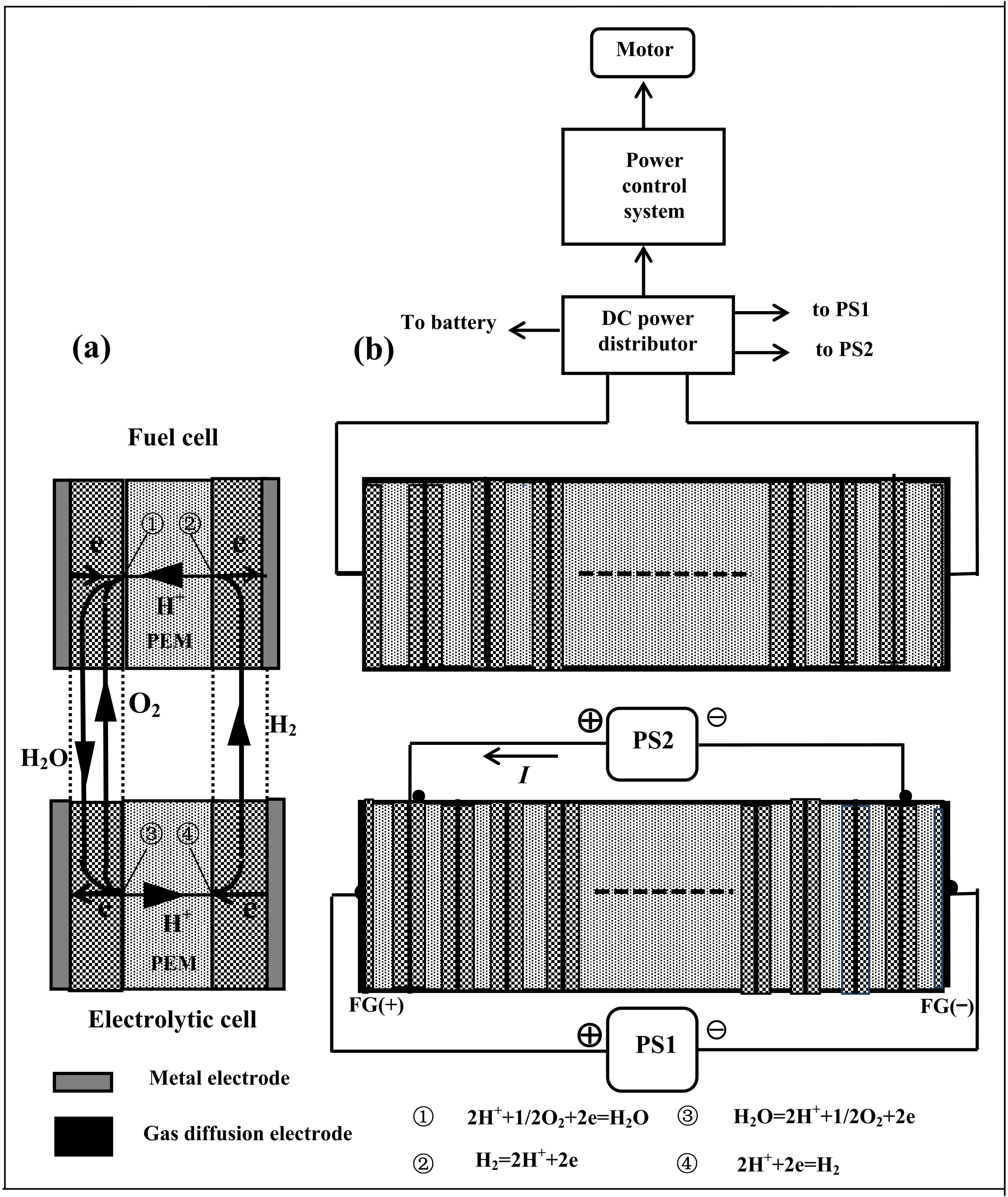

Fig. 5 Schematic diagrams of the on-board HREG propulsion system. (a): Relationship of gas flow directions between PEM EC and PEM FC; (b): Power generation and control systems.

efficiency will increase. However, to ensure that ΔE is low, a large EC surface area is required for a given amount of generated fuel. Therefore, a low ΔE reduces the weight and volume output densities of the HREG system. If we consider the optimal operational conditions, the value of ξ may be 70% [3].

Various operating conditions must be optimized, such as the temperatures of the PEM FC and EC stacks, gas pressures, current densities and the water circulation rate. Stack temperature affects the system durability. Therefore, temperatures above 80 °C are unsuitable for the FC and the EC stacks. The fixed current density of the EC stack automatically determines the magnitude of power output from the FC stack. Because the FC and the EC stacks are located adjacent to each other in the system, the temperature and pressure experienced by both stacks should be approximately equal at less than 100 °C and atmospheric pressure, respectively, to ensure the durability of the cell materials. The gas pressure at the electrodes varies with the equilibrium decomposition voltage of the EC cell and the open circuit voltage of the FC cell. Therefore, it is useful to clarify the relationship between these factors for a wide range of pressures. The associated voltages can be calculated using generalized equations obtained by applying the mass action law applied to H_2 oxidation and reduction. These relationships, which can be derived as functions of gas pressure, p, are as follows:

$$E_{EC} = E_{EC}^{o} + (RT/2F)\ln(p_{H2}p_{O2}^{1/2}) \quad (8)$$

$$E_{FC} = E_{F}-(RT/2F)\ln(p_{H2}p_{O2}^{1/2}) \quad (9)$$

and

$$E_{EC}^{o} + E_{FC}^{o} = 0 \quad (10)$$

where P, E^{o}, R and F denote the gas pressure, standard inter-electrode voltage, gas constant, and Faraday's constant, respectively. For reference, Fig. 6 shows the effect of electrode gas pressure on equilibrium cell voltage. The cell voltage increases as the gas pressure increases. However, the order of increase remains within 0.2 V.

3.3 Mutual Consistency of FC and ESI-PSE Cell with Respect to Performance

Assessments of the on-board HREG system illustrated in Fig. 5 were performed based on the following assumptions and conditions:

(1) The dimensions, structures and materials of the PEM FC and PEM EC cells are exactly the same, and all the individual cells in both the FC and EC stacks must have the same weight and electrode area.

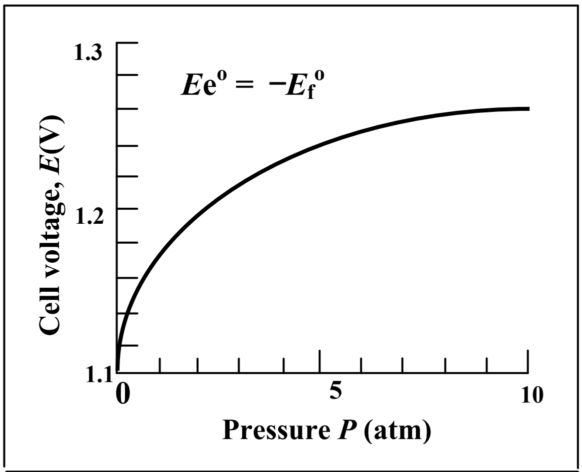

Fig. 6 Theoretical cell voltage as function of gas pressure.

(2) The H_2/O_2 consumption rate in the PEM FC stack and the H_2/O_2 fuel generation rate in the PEM EC stack are equal.

(3) The estimate is given in terms of the weight ratio of the ESI-PSE EC stack responsible for supplying the FC stack with the H_2/O_2 fuel to a typical on-board FC stack, meaning the FC stack currently used for commercial FC vehicles.

Part of the power, P_r, delivered by the PEM FC stack is returned to the PEM ESI-PSE EC stack, and the remaining power represents the actual power used to drive the motor. The cycle power efficiency of the HREG system is defined as:

$$\xi = (P_{net}/P_T) = (P_T\text{-}P_r)/P_T \quad (11)$$

The maximum power output, P_T, of the FC stack must be the sum of the power output from the HREG, P_T^o, plus the power returned from the FC stack to the EC stack, P_r:

$$P_T = P_T^o + P_r \quad (12)$$

From Eqs. (11) and (12) we have

$$P_T = (1/\xi)\ P_T^o \quad (13)$$

The power output of the FC stack is proportional to the number of cells connected in series. Based on the assumption of an FC stack consisting of identical cells, the stack current, I_{FC}, does not depend on the number of cells, N_{FC}, and so an increase in N_{FC} will not change I_{FC}. The FC stack current produces the same magnitude of power in every cell in the stack. According to Faraday's law, the number of moles of H_2 consumed in each cell per unit time will be proportional to I_{FC}, assuming the current efficiencies to be unity. The moles of H_2 consumed in the entire stack must also be proportional to the product $N_{FC} \times I_{FC}$. This amount of H_2 is provided by the PEM EC stack, for which the rate of H_2 emission may be written $N_{EC} \times I_{EC}$. Therefore, from Eq. (13) we obtain the relationship:

$$N_{EC} I_{EC} = (1/\xi) N_{FC}^o\ I_{FC} \quad (14)$$

The currents are related to the current densities, J_{EC} and J_{FC}, as $I_{EC} = A \times J_{EC}$ and $I_{FC} = A \times J_{FC}$, where A is the electrode area. Because the electrode surface area for all cells in the HREG system is the same, Eq. (14) can be written in the form:

$$N_{EC}/N_{FC}^o = (1/\xi)(J_{FC}/J_{EC}) \quad (15)$$

The parameter values used to design the HREG system were as follows:

(1) a cycle power efficiency of 70% ($\xi = 0.7$) [4];

(2) an FC cell voltage, E_{FC}, such as is applied in a typical fuel cell vehicle of 0.7 V [11] rather than the theoretical value of 1.23 V when the car is driven at the maximum power (as a consequence of the remarkable polarization effect in the FC cell);

(3) an extra applied voltage value (ΔE) in Eq. (3) of 0.21 V (such that $E_{EC} = 1.23 + 0.21 = 1.44$ V, where 1.23 V is the water decomposition voltage);

(4) $J_{FC} = 0.50$ A/cm^2 (based on the polarization study [12]);

(5) $J_{EC} = 2.0E_{EC}\text{-}2.4$ (based on the *V-I* relationship, with J_{EC} in A/cm^2 and E_{EC} in volts [13]).

Setting $E_{EC} = 1.44$ V gives $J_{EC} = 0.48$ A/cm^2 from the above equation. Operating the HREG system with $\xi = 0.7$, $J_{FC} = 0.50$ A/cm^2 and $J_{EC} = 0.48$ A/cm^2, the N_{EC}/N_{FC}^o ratio becomes 1.49, based on Eq. (15). These calculations indicate that the number of cells required for the ESI-PSE EC stack will be 1.5 times the quantity in a typical FC stack if the HREG system is to be self-reliant.

3.4 Gross Weight Evaluation of an On-board HREG

The first requirement in a theoretical investigation of an on-board HREG system is to determine its applicability to FC vehicles. One aspect of predicting the possibility of transportation applications is the gross weight of the unit. Because the stack weight is proportional to the number of cells in the stack and the rate of H_2 consumption equals the rate of H_2 generation, the weight ratio of the EC stack to that of a typical FC stack is given by:

$$M_{EC}/M_{FC}^o = N_{EC}/N_{FC}^o = I_{FC}/I_{EC} \quad (16)$$

Hence,

$$M_{EC} = (J_{FC}/J_{EC})\ M_{FC}^o \quad (17)$$

To evaluate the total weight, M_T, of the HREG system, M_T must be related to the weight of a typical

FC stack, M_{FC}^{o}, through a non-dimensional factor, α, as:

$$M_T = \alpha M_{FC}^{o} \quad (18)$$

Using Eqs. (12) and (13), we obtain:

$$P_r = [(1\text{-}\xi)/\xi]\ P_T^{o} \quad (19)$$

It follows that:

$$N_{FC}^{(r)} = [(1\text{-}\xi)/\xi]\ N_{FC}^{o} \quad (20)$$

If the number of cells is proportional to the weight, then Eq. (20) may be replaced by:

$$M_{FC}^{(r)} = [(1\text{-}\xi)/\xi]\ M_{FC}^{o} \quad (21)$$

Therefore, the total weight of the HREG system can be obtained using Eqs. (17) and (21) as:

$$M_T = M_{FC}^{o} + M_{FC}^{(r)} + M_{EC} = \alpha M_{FC}^{o} \quad (22)$$

where α is a factor given by:

$$\alpha = 1 + (1\text{-}\xi)/\xi + (J_{FC}/J_{EC}) \quad (23)$$

Thus, α becomes a non-dimensional weight factor. During the numerical evaluation of the total weight of an on-board HREG system to determine its viability in a standard passenger vehicle, α value may be used as an index for weight and volume. The value calculated in this work using $\xi = 0.7$, $J_{EC} = 0.48$ A/cm^2 and $J_{FC} = 0.50$ A/cm^2 was $\alpha = 2.47$. At present, a typical on-board FC stack has a weight on the order of 60 kg. Therefore, the HREG system will weigh 2.47 × 60 = 148 kg. However, the weight of the HREG system does not actually exceed that of existing FC units, because this FC unit weight includes the FC stack (60 kg) plus a high pressure hydrogen tank (100 kg), for a total of 160 kg. Although the present evaluation is preliminary in nature, the results herein suggest that new propulsion system based on the HREG could be applicable to regular passenger vehicles.

4. Propulsion System

4.1 System Outline

The following major characteristics were used as criteria to establish the nature of this type of propulsion system.

(1) Direct steady state extraction of full power from the FC for controller is required; a full power is drawn from the FC at all the times. The controller delivers zero power when the vehicle is stopped; therefore, full power is wasted in the controller. However, there is no energy loss in the HREG side owing to its self-sustaining nature in terms of energy.

(2) The on-board HREG may be designed to only deliver the maximum power required by the motor, i.e., maximum design power. The steady state operation will be established spontaneously owing to the invariable power condition.

(3) The conventional definition of energy efficiency cannot be applied to the present PCS, because the electrostatic energy created internally in the EC is responsible for the power output of the HREG. Here, the power cycle efficiency is defined as an index of the power generation efficiency. It is the ratio of the net power output from the FC's to the total power generated by the FC''s.

The propulsion system (Fig. 5) for providing optimum performance for achieving infinite driving range will require specific operational conditions for both the HREG and the PCS as well as mutual consistency between them. First, it is assumed that the FC stack provides the PCS with the maximum power, $P_{M(max)}$, required by the motor to run at its top speed continuously. This may be expressed as follows:

$$P_{M(max)} = I_{FC}\ V_{FC} \quad (24)$$

and

$$R_M I_{FC} = V_{FC} \quad (25)$$

where I_{FC} and V_{FC} are the current and the voltage delivered from the FC stack, respectively and R_M is the resistance of motor. In the case of a conventional FCV, the maximum motor power is 120 kW, and the FC voltage is increased up to 650 V using a boost converter, so that I_{FC} = 185 A.

4.2 Power Control System

In conventional EVs and FCEVs, DC electricity is fed into a DC/AC inverter where it is converted into AC electricity and this AC power is connected to an AC motor via an electronic control system [14, 15]. During this process a certain percentage of energy is lost as heat. Therefore, in the case of EVs and FCEVs that depend on off-board energy sources (electricity and hydrogen), the energy efficiency of the PCS is always a challenge. At reduced speeds, when full power is not needed, a certain percentage of the energy from the FC is definitely wasted. However, the on-board HREG system can be used to realize an energy loss-free PCS. With such a system, energy wasted in the PCS does not cause any energy loss, because the full power is created inside the closed energy cycle HREG without the introduction of any external energy.

As a simple example to demonstrate there is no power loss in this propulsion system, a variable-resistor-type PCS for a DC motor is shown below, regardless of the cooling scheme. Fig. 7 shows a navigation system comprising VR1 and a by-pass variable resistor VR2. Its performance characteristics may be described by the following circuit analysis:

If the resistances of VR1 and VR2 are set to zero and the maximum resistance, i.e., $R_1 = 0$ and $R_2 = R_{max}$, respectively, then the full current, I_{FC}, flows through the motor. In this stage, the car runs at its top speed.

If the resistances VR1 and VR2 are set to $R_1 = R_{max}$ and $R_2 = R_M$, respectively, the current through the motor becomes zero, and the car stops. The full current, I_{FC}, flows through VR2. The current, I_{FC}, flows constantly, regardless of vehicle speed. Therefore, the resistance between a and b in Fig. 7 must equal R_M. Accordingly, we must have;

$$1/R_M = 1/(R_M+R_1)+1/R_2 \quad (26)$$

This may be written in the form

$$R_2 = R_M+R_M^2/R_1 \quad (27)$$

If the driver uses an accelerator pedal linked to a potentiometer, it provides the regulator with the signal for controlling the resistances of two variable resistors to move along the R_1-R_2 curve as shown in Fig. 8a.

The voltage applied to the motor, V_M, is related to the resistance of VR1 as

$$V_M = V_{FC}R_M/(R_M + R_1) \quad (28)$$

This relationship is presented graphically in Fig. 8b. A part of the power provided by the FC is used by the motor, and the remainder is wasted as Joule heat from the resistors when vehicle is in motion.

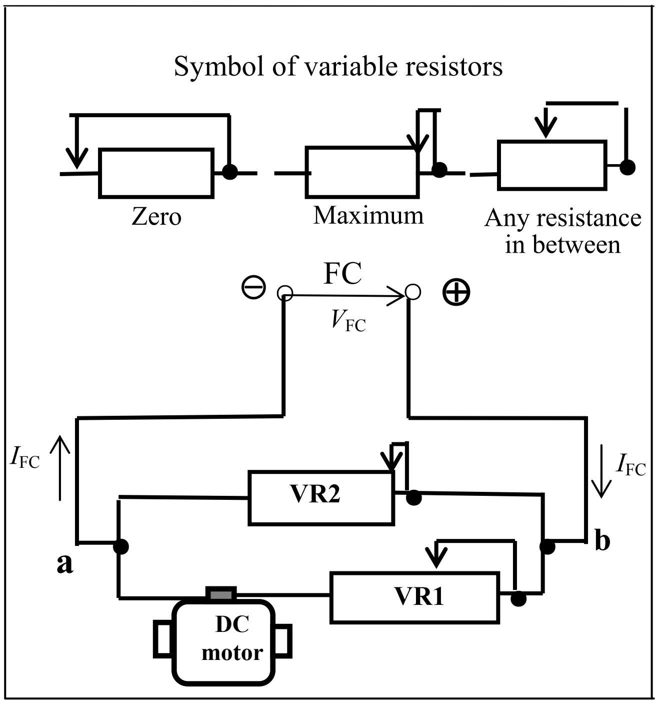

Fig. 7 Circuit diagram for variable-resistor-type power control of FCV at the travelling stage. V_{FC}: FC output voltage; I_{FC}: FC delivering current; VR: variable resister.

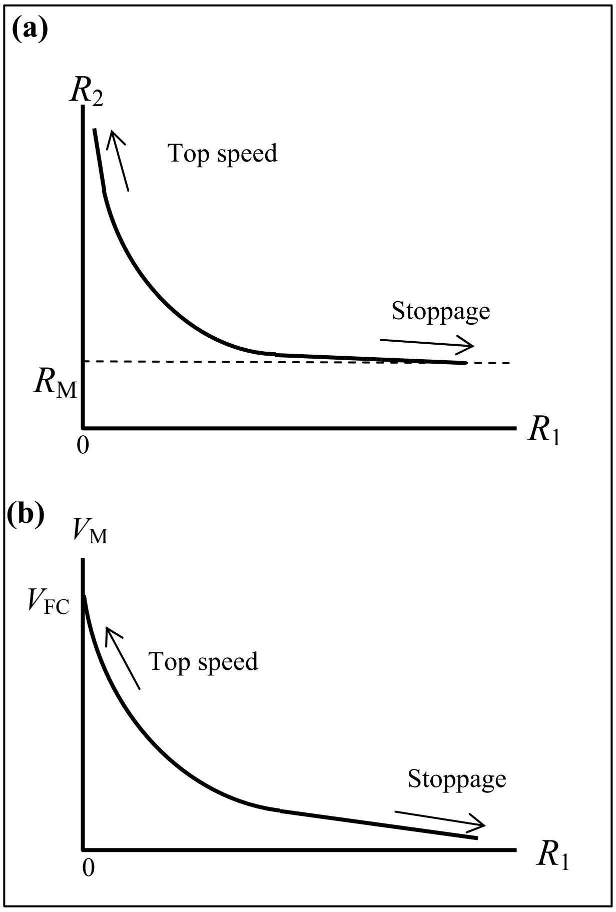

Fig. 8 R_1-R_2 curve (a) and V_M–R_1 curve (b).

To stop a vehicle, simultaneous shutdown of the voltages, V_{PS1}, V_{PS2} and V_{FC} is performed using a switch for cutting off the current, I_{FC}, through the circuit between the FC and the DC power distributor shown in Fig. 5b. To bring the system up to the power required to start the vehicle, the procedure is essentially as follows: the switch is closed again to return to the stoppage mode, and the battery is used to provide the powers PS1 and PS2 briefly: the theoretical battery power equals P_r.

5. Conclusion

In this study, we theoretically examined possibilities for creating new propulsion system for FC vehicles with the purpose of providing a potentially unlimited driving range. According to the proposed approach, the PEM FCs and the PEM ESI-PSE ECs are consolidated into a HREG system. The HREG is designed to deliver a time-invariable magnitude of power equal to the motor's maximum power at all times when the vehicle is in motion (mono power output operation of the HREG). The energy-loss-free mechanism of this propulsion system is based on the energetically self-sustaining performance of the HREG. "Zero power input" electrostatic energy observed in the ESI-PSE is responsible for the real power output of the HREG. Thus, the proposed system does not violate the energy conservation law and is consequently not related to the perpetual motion machine. We have performed a performance simulation of the proposed propulsion system and confirmed its theoretical feasibility. Expectedly, this type of propulsion system can be applied to other modes of transportations, such as buses, trucks, and railway trains.

References

[1] Ono, K. 2013. "Fundamental Theories on a Combined Energy Cycle of Electrostatic Induction Hydrogen Electrolytic Cell and Fuel Cell to Produce Sustainable Hydrogen Energy." *IEEJ Trans. on Fundamentals and Material* 133 (12): 615-21.

[2] Ono, K. 2015. "Energetically Self-sustaining Electric Power Generation System Based on the Combined Cycle of Electrostatic Induction Hydrogen Electrolyzer and Fuel Cell." *IEEJ, Trans. on Fundamentals and Materials* 135 (1): 22-33.

[3] Ono, K. 2015. "Theoretical Concept of Hydrogen Redox Electric Power Generation." *IEEJ Trans. on Fundamentals and Materials* 135 (8): 456-66.

[4] Ono, K. 2016. "Hydrogen Redox Electric Power and Hydrogen Energy Generators." *International Journal of Hydrogen Energy* 41: 10284-91.

[5] Ono, K. 2017. "Theoretical On-board Hydrogen Redox Electric Power Generator for Infinite Cruising Range Fuel Cell Vehicles." *Journal of Energy and Power Engineering* 11: 646-54.

[6] Floyd, T. L. 2004. *Electronics Fundamentals.* New Jersey: Peason Education.

[7] Weir, W. J. 1987. *Electronic Circuit Fundamental.* New Jersey: Prentice-Hall INC.

[8] Smith, R. A. 1971. *Semiconductors.* Tokyo: McGraw Hill Kogakusha.

[9] Sze, S. M. 1969. *Physics of Semiconductor Devices.* New York: Wiley International Edition.

[10] Vielstich, W., Lamm, A., and Gasteiger, H. A. 2004. *Handbook of Fuel Cells.* New Jersey: John Wiley & Sons Ltd.

[11] Takahashi, Y. 2017. *Book on Fuel Cell Vehicles.* Tokyo: Denki-shoin.

[12] Barbir, F. 2013. *PEM Fuel Cells, Theory and Practice.* Amsterdam: Elsevier.

[13] Annual Report. *National Resources and Energies 1999/2000.* The Agency for Resources and Energies, Japan.

[14] Bonnik, A. W. M. 1998. *Vehicle Electronic Systems and Fault Diagnosis.* London: Arnold.

[15] Datta, S. K. 1985. *Power Electronics and Controls.* Verginia: Reston Publishing Co., Inc.