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Journal of Power Sources 115 (2003) 203–209
JOURNAL OF POWER SOURCES
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The characteristics of power generation of static state fuel cells

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Received 17 September 2002; received in revised form 25 November 2002; accepted 2 December 2002

Abstract

In this work, we find a regulation of electric power generation of static state fuel cells. This regulation is described as: *Total electric power of static state fuel cells is proportional to the square of potential difference between thermodynamic equilibrium potential and export potential*. With this regulation we derive an equation to describe the performance curve of static state fuel cells. There are two main parameters in the equation: one is power convert coefficient of fuel cell: K; another is fuel cell inner resistant: R. With these parameters, we can evaluate fuel cell more clearly and easily. The equation is verified with different kinds of direct methanol fuel cells and gives out the capacity of fuel cell is related to the inner resistant and chemical reaction. This regulation is also fit to fuel cells in series and parallel group.

Keywords: Fuel cell; Power generation; Regulation; Parameter; Power convert; Coefficient; Inner resistant

1. Introduction

Fuel cells are commercially viable power sources for portable and transportation application [1,2]. To evaluate the characteristics of a fuel cell, the conventional way is with potential against current performance curves. Fig. 1 is the electric circuit to test the performance curve. Fig. 2 shows a typical current–voltage performance curve of a low temperature fuel cells [3]. Current theory describes [4]: There are three distinct regimes in fuel cell performance curve: at low cell currents, in region (A), the cell voltage is dominated by the electrochemical kinetics which is called the activation controlled current density region. By increasing the current load, the cell voltage is further decreased due to the inner resistance of the fuel cell in region (B), which is called Ohmic controlled current density region. In region (C), the system approaches a limiting current density at which the cell voltage breaks down. The level of the limiting current density mainly depends on reactant mass transport. In this paper, we describe the capacity of fuel cell with inner resistant and power convert capacity by chemical reaction. As a chemical power source, a fuel cell finally reflects on its burden as its inner resistant and its power convert capacity. We use one regulation and its equation to summarise all three regimes. The activation, Ohmic and mass transfer control finally give out overall different inner resistant or different power convert capacity in operate current. In some fuel cells, the region (C) is not obviously, or for the reason of simplification, the region (C) is not considered. Fig. 3 shows the performance curve [5] without region (C). In this paper, we call this kind of fuel cell the first type fuel cell and as the second type fuel cell with performance curve with region (C).

To evaluating the characteristics of fuel cells or to interpret the fuel cell potential against current density behaviour, many modelling studies exist [6–17], carried out to elucidate the electrochemical behaviour of fuel cells especially in polymer electrolyte fuel cell (PEFC).

For the first type fuel cell, the cell voltage against current density behaviour, in activation and Ohmic controlled current density region, can be described by the relationship [11]:

$$V = E_0 - b\log i - Ri \quad (1)$$

where $E_0 = E_r + b\log i_0$ and E_r is the reversible potential of the cell, i_0 the exchange current density, b the Tafel slope of for example oxygen reduction and R represents the resistance.

For the second type fuel cell, Eq. (1) was modified by Kim et al. [17] by introducing an additional term as follows:

$$V = E_0 - b\log i - Ri - m\exp(ni) \quad (2)$$

where the parameters m and n are derived from mathematical and statistical considerations.

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doi:10.1016/S0378-7753(02)00731-0

Nomenclature

E	fuel cell potential (V)
E_e	equivalent potential of fuel cells group (V)
E_0	thermodynamic equilibrium potential of fuel cell (V)
I	export current density (A cm^{-2})
K	power convert coefficient of fuel cell (Ω^{-1})
K_e	equivalent power convert coefficient of fuel cells group (Ω^{-1})
P	export power of fuel cell (W)
P_{total}	total electric power of fuel cell system (W)
R	inner resistance (Ω)
R_0	inner resistance in low operate current (Ω)
R_e	equivalent inner resistance of fuel cells group (Ω)
V	export voltage (V)

Squadrito et al. [18] modified Eq. (2) as:

$$V = E_0 - b \log i - Ri + \alpha i^k \ln(1 - \beta i). \tag{3}$$

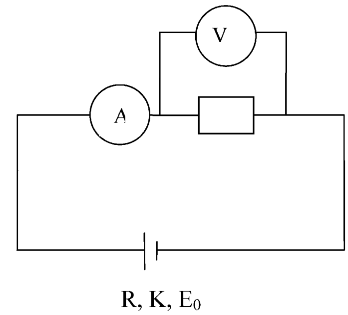

Fig. 1. The electric circuit to test performance curve.

Here, the logarithmic term $\ln(1 - \beta i)$ in Eq. (3) introduces a limit in the available current density for better modelling results.

Although those studies can give good modelling results for specific fuel cell performance curves, they need a change in parameters to model other kinds of fuel cells.

Theoretical models based on mechanistic approaches frequently require the knowledge of too many parameters such as humidity levels, transfer coefficients, thickness of

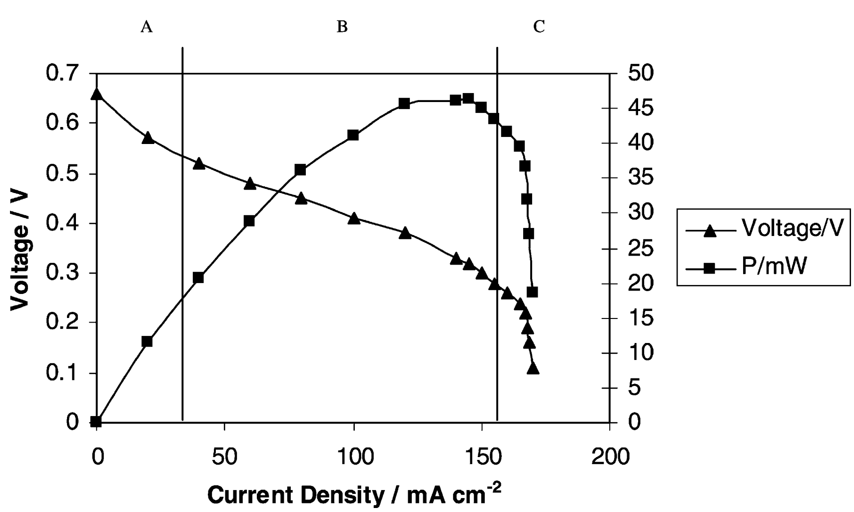

Fig. 2. Performance curve of second type fuel cell [3].

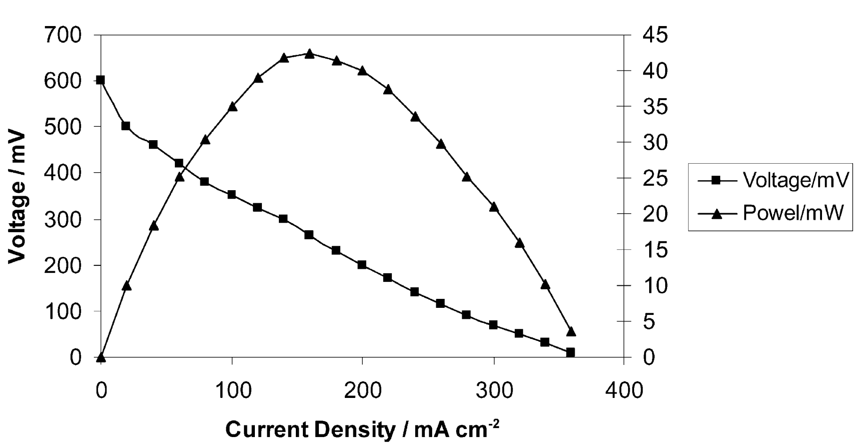

Fig. 3. Performance curve of first type fuel cell [5].

membrane gradients of temperature and pressure and solution concentration, etc. [6,7,11,14]. Many parameters are not available for any kind of PEFC fuel. Other parameters have no specific physical meanings but are used for numerical adjustment [18] and depend on empirical modification.

As an electrical power source, the electrical characteristics of fuel cell can be clearly evaluated by an export potential–current performance curve. But with potential–current performance curve, previous work can not decide all those parameters in modelling equations. Besides, with these empirical mathematical equations, we can not easily and directly tell the characteristics and performance of a fuel cell.

For above reasons, we investigate the characteristics of static state fuel cell with the first type fuel cell. We found the regulation of electrical power generation of the DMFC fuel cell and other static state chemical electrical power source. With this regulation, we derive an equation to describe the static state performance curve of the first kind of fuel cell. There are two main parameters in the equation. One is power convert coefficient of fuel cell: K; the other is the fuel cell inner resistant: R. With these parameters we can describe characteristics and capacity of fuel cell more easily and clearly. For the second type fuel cells, we consider the inner resistant to increase with operate current. The mathematical equation can model the performance curves of second type fuel cell very well. With this regulation, we also derive the equations to describe fuel cells in series and parallel group.

2. Regulation of electrical power generation of static state fuel cells

In an electrical circuit, the important characteristics of power source are the inner resistance and export voltage. The export voltage conventionally changes with operating current. This relationship gives capacity of a power source to support the electrical power which is expressed by the voltage and current performance curve.

For investigating the power support capacity of fuel cell, here we consider the fuel cell process at the static state, i.e. operating conditions such as: temperature, solution concentration and pressure are not changed with time. Before discussing the second type fuel cell, we investigate the first type of fuel cell. Fig. 1 is the circuit to measure the performance curve of fuel cell.

Here, export power of fuel cell is

$$P = I \times V. \tag{4}$$

If the inner resistant of fuel cell is R, which can be get from performance curve, then the total electrical power converted by fuel cell is P_{total}, the total electrical power converted by a fuel cell should include the export power and the power consumed in the inner resistant. So,

$$P_{\text{total}} = P + I^2R = IV + I^2R. \tag{5}$$

Here, we find the regulation of electric power generation of static state fuel cells as: total electric power of static state fuel cells is proportional to the square of potential difference between the potential of fuel cell in thermodynamic equilibrium and export potential. Namely,

$$P_{\text{total}} = K(E_0 - V)^2 \tag{6}$$

where K is proportional coefficient.

Compare Eqs. (5) and (6):

$$IV + I^2R = K(E_0 - V)^2. \tag{7}$$

When $I = 0$,

$$V = E_0. \tag{8}$$

Fig. 4 [19] shows performance curves of four different fuel cells. According to performance curve data in Fig. 4 and Eq. (5), we plot P_{total} against $(E_0 - V)^2$ in Fig. 5.

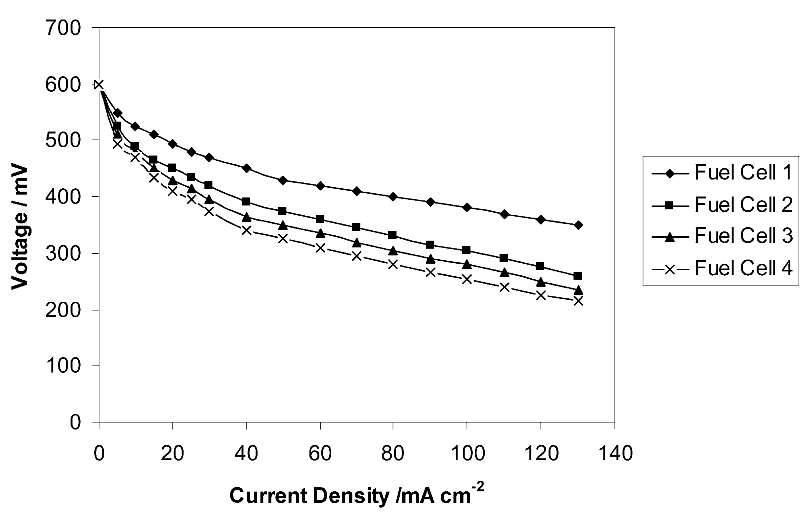

Fig. 4. Performance curves of different fuel cells [19].

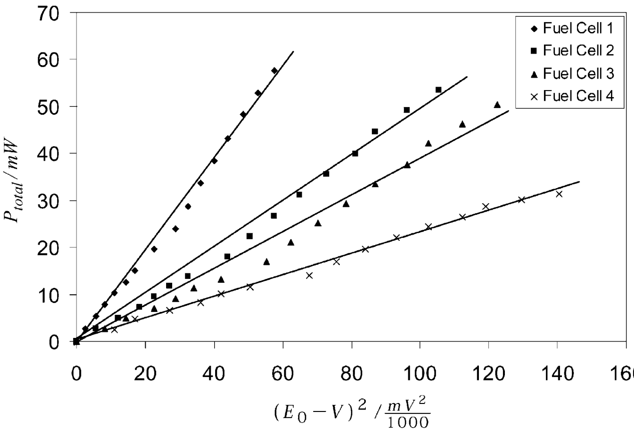

Fig. 5. Plots of P_{total} against $(E_0 - V)^2$.

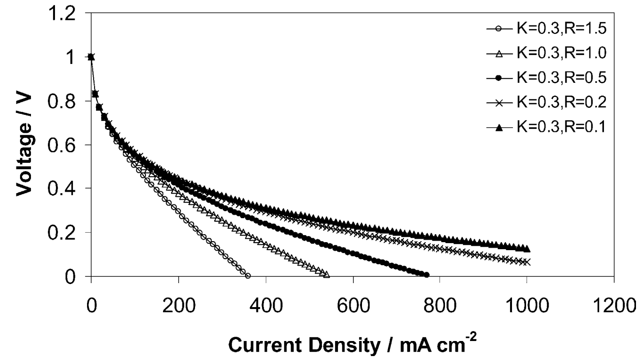

Fig. 6. Numerical results of performance curve of first type of fuel cell.

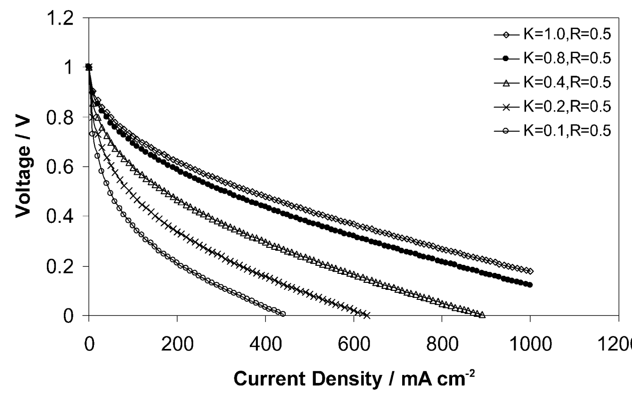

Fig. 7. Numerical results of performance curve of first type of fuel cell.

Fig. 5 shows that P_{total} has a linear relationship with $(E_0 - V)^2$ which prove the regulation of electrical power generation of static state fuel cells. The slope is K which represents the capacity of power converted by a fuel cell. In most static state fuel cells, the K is constant in operation. Here, we definite ideal fuel cell is a fuel cell with constant K and constant resistant R during its operation. Ideal fuel cell is also the first type fuel cell.

3. The performance curve equation and its numerical characteristic

If K and R are constants, from Eq. (7):

$$V = E_0 + \frac{I - \sqrt{I^2(1 + 4KR) + 4KIE_0}}{2K}. \tag{9}$$

Fuel cell potential is

$$E = V + IR,$$

$$E = E_0 + IR + \frac{I - \sqrt{I^2(1 + 4KR) + 4KIE_0}}{2K}. \tag{10}$$

Export power of fuel cell is

$$P = I \times V,$$

$$P = E_0 I + \frac{I - \sqrt{I^2(1 + 4KR) + 4KIE_0}}{2K} \times I. \tag{11}$$

Total power of fuel cell is

$$P_{total} = P + I^2 R,$$

$$P_{total} = E_0 I + I^2 R + \frac{I - \sqrt{I^2(1 + 4KR) + 4KIE_0}}{2K} \times I. \tag{12}$$

When $V = 0$,

$$I_{max} = E_0 \sqrt{\frac{K}{R}}. \tag{13}$$

From the Eq. (9), we can make the curve of export potential against current. Figs. 6 and 7 show numerical modelling results of performance curve with different fuel cell coefficients. In Fig. 6, $E_0 = 1.0$, $K = 0.3$, $R = 0.2$–1.5; in Fig. 7, $E_0 = 1.0$, $K = 0.1$–1.0; $R = 0.5$. The plot shapes are very close to the performance curve of first type of fuel cell. From view point of numerical modelling, we can adjust the value of parameters K and R to change the curve degree and line slope to fit the practical performance curve of fuel cell. In another word, Eq. (9) can express and model the performance curve of first type of fuel cell.

4. Calculate the fuel cell coefficients K and R and modelling results of first type of fuel cell

From Eq. (7):

$$\frac{V}{I} = K\left(\frac{E_0 - V}{I}\right)^2 - R \tag{14}$$

which is a linear relationship between V/I and $((E_0 - V)/I)^2$, The slop is K and the intercept is R.

With the data from Fig. 3 [5], we get the linear plot in Fig. 8. Here, the parameters of this fuel cell in Fig. 3 are: $K = 1.14$ (Ω^{-1}), $R = 3.39$ (Ω).

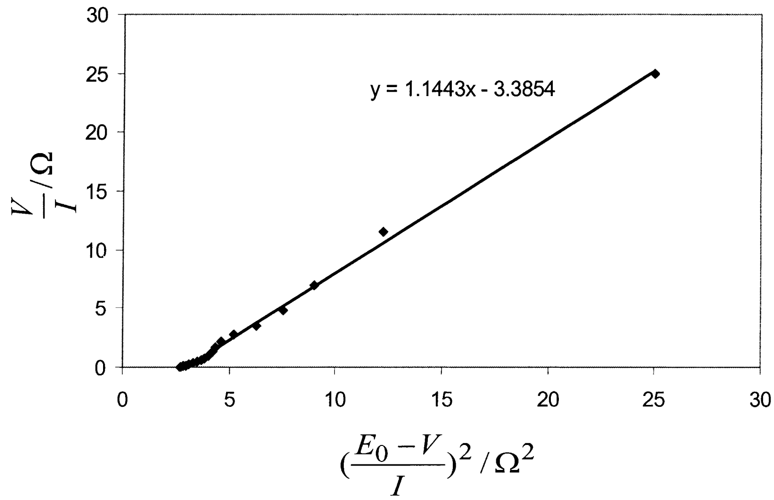

Fig. 8. Plot of V/I against $((E_0 - V)/I)^2$.

Using $K = 1.14$, $R = 3.39$ and $E_0 = 0.6$ into Eqs. (9) and (11), the modelling results in Fig. 9, agree with experiment data very well.

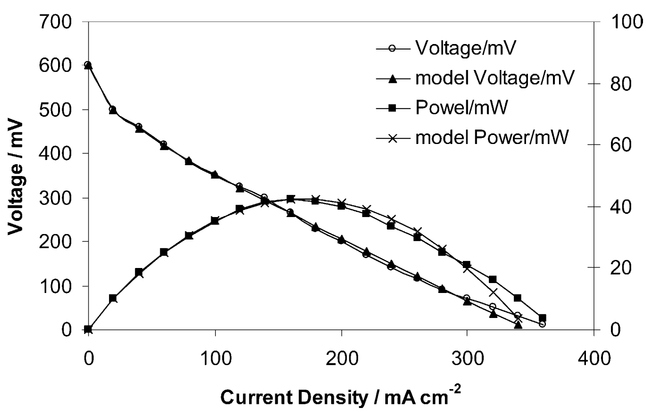

Fig. 9. Modelling and experiment results of first type of fuel cells.

5. Discussion of second type fuel cells

When fuel cell parameters K and R change with operation current, we call it non ideal fuel cell. In most static state fuel cell, because the operation condition does not change in operation, the property of kinetic electrochemical reaction will be same. So, the power convert coefficient K of fuel cell is a constant. But, the inner resistance R of fuel cell is no more a constant. R will change with current I. Fig. 2 is a typical performance curve of the second type fuel cell. So, when modelling second type fuel cells, we need to consider and modify the value of the inner resistance of fuel cells.

There are three distinct regimes in the performance curve of the second type fuel cell. In the regions A and B of Fig. 2, the value of the inner resistance is almost a constant. So, we can use Eq. (14) to determine the fuel cell parameters of the second type fuel cell. Fig. 10 shows the plot of V/I against $((E_0 - V)/I)^2$ in the regions A and B at the low operation

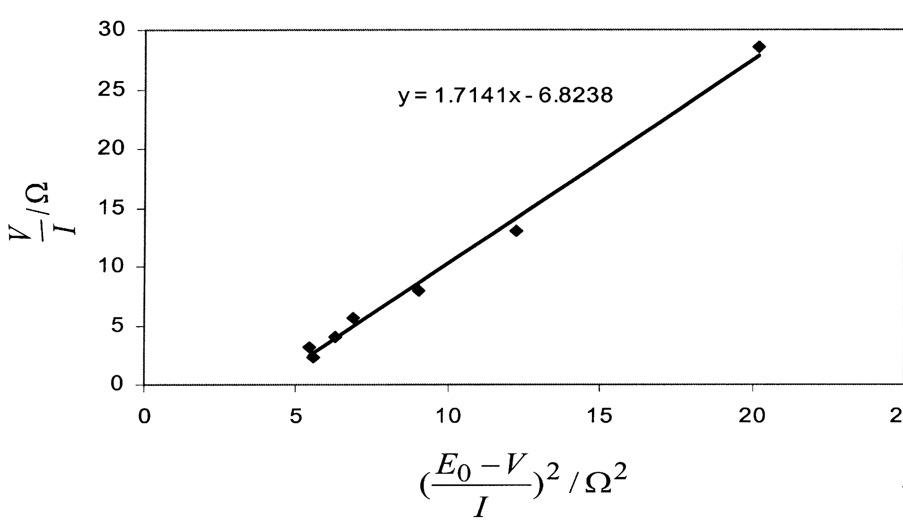

Fig. 10. The plot of $V/I \sim ((E_0 - V)/I)^2$ of second type of fuel cell in low current.

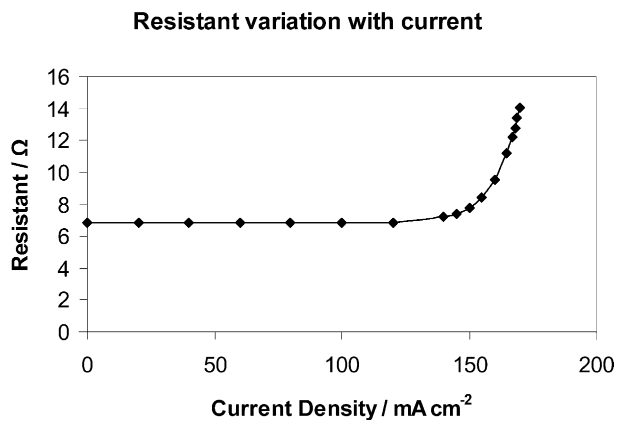

Fig. 11. Resistance variation with current in second type fuel cell.

current of the fuel cell in Fig. 2 [3]. The fuel cell parameters are: $R_0 = 6.82\ \Omega$, $K = 1.71\ \Omega^{-1}$.

Because the value of inner resistance of the second type fuel cell will increase with current in region C, we need to modify the value of inner resistance before applying the resistance value in the Eq. (9).

The value of electrolyte resistance can be expressed as below:

$$R = R_0 + \alpha\,\mathrm{e}^{\beta I} \tag{15}$$

where R_0 is the resistance value in low operation current; α, β the empirical coefficients; I the operate current density.

Using $R_0 = 6.823$, $\alpha = 3 \times 10^{-7}$, $\beta = 100$ to modify the value of inner resistance of second type fuel cell.

$$R = 6.823 + 3 \times 10^{-7}\,\mathrm{e}^{100I}. \tag{16}$$

Fig. 11 shows the value of inner resistance changes with current of Eq. (16).

With the data of Figs. 2 and 10, we apply $K = 1.71$, $E_0 = 0.66$ and $R = 6.823 + 3 \times 10^{-7}\,\mathrm{e}^{100I}$ in Eq. (9) and obtain the modelling results of second type fuel cell shown in Fig. 12. The modelling results agree with experimental results very well.

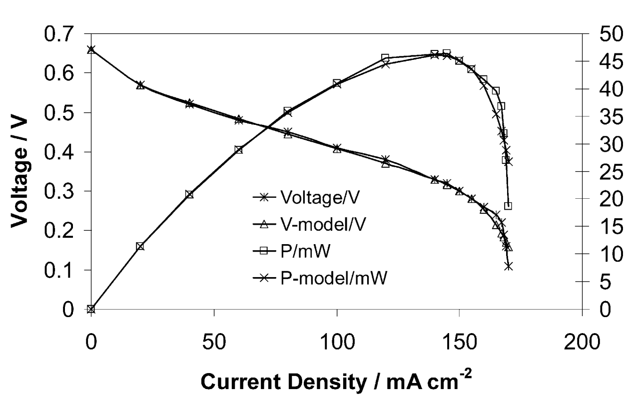

Fig. 12. Modelling and experiment results of second type of fuel cells.

6. The characteristics of fuel cells group with series and parallel connection

When two identical fuel cells are connected in series group as Fig. 13, or in parallel group as Fig. 14, the performance curve can express the characteristics of fuel cells group.

If single fuel cell parameters are R, K and E_0, Apply the regulation of electric power generation in fuel cell group, we can get the function of the performance curve of fuel cells group as below:

$$V = E_\mathrm{e} + \frac{I - \sqrt{I^2(1 + 4K_\mathrm{e}R_\mathrm{e}) + 4K_\mathrm{e}IE_\mathrm{e}}}{2K_\mathrm{e}}. \tag{9b}$$

Here, the parameters of fuel cells group are: E_e, K_e and R_e which can be acquired from the parameters of single fuel cells E_0, K and R.

For two fuel cells series group:

$$R_\mathrm{e} = 2R, \quad E_\mathrm{e} = 2E_0, \quad K_\mathrm{e} = \frac{K}{2}. \tag{17}$$

For n fuel cells series group:

$$R_\mathrm{e} = nR, \quad E_\mathrm{e} = nE_0, \quad K_\mathrm{e} = \frac{K}{n}. \tag{18}$$

For two fuel cells parallel group:

$$R_\mathrm{e} = \frac{R}{2}, \quad E_\mathrm{e} = E_0, \quad K_\mathrm{e} = 2K. \tag{19}$$

For n fuel cells parallel group:

$$R_\mathrm{e} = \frac{R}{n}, \quad E_\mathrm{e} = E_0, \quad K_\mathrm{e} = nK. \tag{20}$$

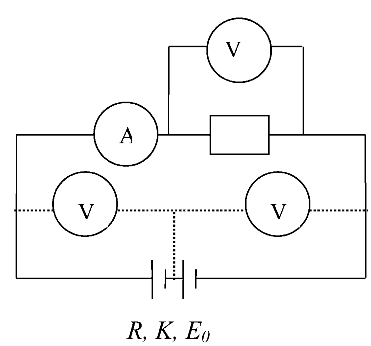

Fig. 13. Two series fuel cells group.

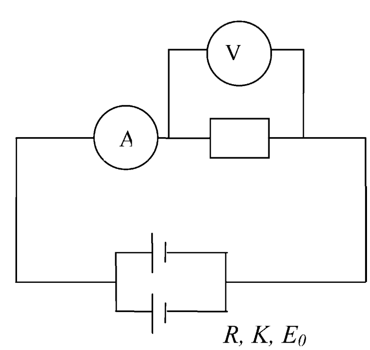

Fig. 14. Two parallel fuel cells group.

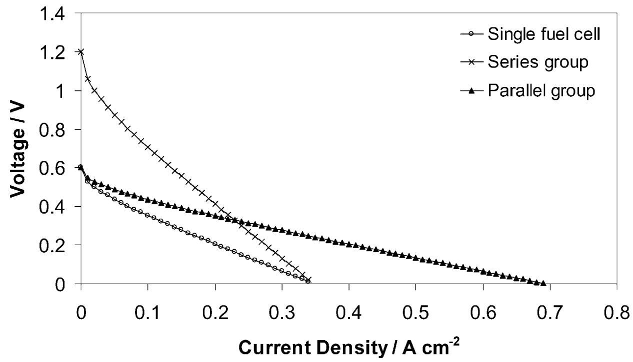

Fig. 15. Performance curves of first type fuel cells group $K = 1.14\ \Omega^{-1}$, and $E_0 = 0.6$ V, $R = 3.39\ \Omega$.

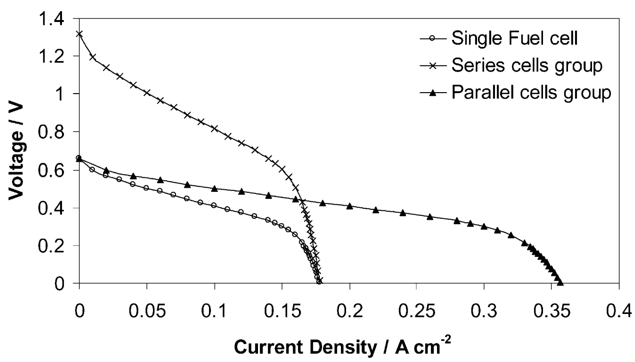

Fig. 16. Performance curves of second type fuel cells $K = 1.71\ \Omega^{-1}$, $E_0 = 0.66$ V, $R = 6.823 + 3 \times 10^{-7}\, e^{100I}\ \Omega$.

Figs. 15 and 16 show model results of performance curves of the fuel cells group which express the relationship between fuel cells group and single fuel cell clearly.

7. Conclusion

1. The regulation of electrical power generation of static state fuel cells is in existence and proved through different kinds of fuel cells.
2. The characteristics and capacity of fuel cell and fuel cells group can be described with power convert coefficient K and inner resistance R.
3. Mathematical equations have been developed to express performance curves of fuel cells and fuel cells group.

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