Performance improvement of a Microbial fuel cell based on adaptive fuzzy control

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Abstract: Microbial fuel cells have been obtaining more and more attention with the associated abilities of continuous electrical power supply and wastewater treatment. Because of its complicated reaction mechanism and its inherent characteristics of time varying, uncertainty, strong coupling and nonlinearity, there are complex control challenges in microbial fuel cells. In this paper, an adaptive fuzzy control scheme is proposed for the microbial fuel cell system to achieve constant voltage output under different loads. A main fuzzy controller is used to track the set value, and an auxiliary fuzzy controller is applied to adjust the factors of the main controller. Simulation results show that the output voltage can track the given value well. The proposed adaptive fuzzy controller can give better steady-state behavior and faster response, and it improves the running performance of the microbial fuel cell.

Keywords: Microbial fuel cell, adaptive, fuzzy control, constant voltage.

INTRODUCTION

The impending energy crisis and global warming warrant the need for eco-friendly sources of energy (Chirag *et al.*, 2013). Choosing a clean energy future will increase human's independence, reinvigorate our economy with new jobs and make the environment cleaner and safer.

Microbial fuel cells (MFCs), which transform chemical energy directly into electrical energy, represent a clean and renewable energy resource (Zhou *et al.*, 2013 and Lovley 2006). It is a promising technology for wastewater treatment with simultaneous bioenergy production (Liu *et al.*, 2006; Du *et al.*, 2007 and Zhang *et al.*, 2013). It is being developed to monitor environmental systems such as rivers and oceans (Bond *et al.*, 2002 and Zhang *et al.*, 2011). MFCs are suitable for using as power supply to remote sensors (Ren *et al.*, 2007 and Logan *et al.*, 2006). Another potential application of the MFC technology is to use it as a sensor for pollutant analysis and in situ process monitoring and control (Chang *et al.*, 2004 and Shen *et al.*, 2012).

MFCs have not been commonly considered as the energy supplying ways for the future despite their outstanding advantages because MFC-based technology is not sufficiently advanced enough to produce substantial quantities of energy in a cost-effective manner (Kim *et al.*, 2008). The remaining problems mean that it is still long way before they can successfully replace a various traditional energy systems. The challenge needs a multidisciplinary approach to break through the bottlenecks of the MFC performance. Obviously, the automatic control plays an important role in the aspect of improving the performance of MFCs.

Some inherent obstacles exist in the application of microbial fuel cells. Low output voltage that varies with age and current, reduced efficiency with slow response to a load step response, no acceptance of reverse current and no overload ability provide many technical challenges that must be overcome by voltage conditioning systems including a good control system (Yu *et al.*, 2007).

The microbial fuel cell system cannot lead to acceptable responses by using traditional controllers as a result of its time-change, uncertainty, strong-coupling and nonlinear characteristics. So an adaptive or intelligent controller is needed to direct at the characteristics of MFC system (Rezazadeh *et al.*, 2010). Fuzzy logic provides a certain level of artificial intelligence to the conventional controllers. Fuzzy logic control features such valuable merits as universal approximation theorem, rule-based algorithm, and robustness with respect to plant parameter uncertainties (Galzina *et al.*, 2008 and Corcau *et al.*, 2007). However, the price being paid for that of an undesirable phenomenon called steady-state error and it relies on experience excessively. Adaptive control is considered to be a useful tool for reducing steady-state error because of its capability of seeking the optimal control parameters automatically to resist load disturbance. Adaptive fuzzy control utilizes fuzzy control to overcome the influence of plant parameter uncertainties, and utilizes adaptive control to decrease steady-state error caused by fuzzy control. Therefore, it improves rapidity and stationary in dynamic response of the system.

In this paper, a dynamic system of microbial fuel cell is modeled and an adaptive fuzzy controller is designed to control the MFC system to maintain a constant output voltage.

Dynamic model of MFC

The origin of voltage in MFC can be understood by considering the chemical reactions occurring at cathode

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Corresponding author: e-mail: flpsd@163.com and anode compartments given as follows (Lee *et al.*, 2008 and Torres *et al.*, 2008):

$$(CH_2O)_2 + 2H_2O \rightarrow 2CO_2 + 8H^+ + 8e^- \quad \text{(Anode)} \quad (1)$$

$$O_2 + 4e^- + 2H_2O \rightarrow 4OH^- \quad \text{(Cathode)} \quad (2)$$

The output voltage V_{mfc} of a single microbial fuel cell can be described as the following equation :

$$V_{\mathrm{mfc}} = V_0 - \eta_{\mathrm{a}} - \eta_{\mathrm{c}} - \left(\frac{d_{\mathrm{mfc}}}{k_{\mathrm{aq}}} + \frac{d_{\mathrm{m}}}{k_{\mathrm{m}}}\right) i_{\mathrm{mfc}} \quad (3)$$

where V_0 is the voltage of open-circuit; d_{mfc} and d_{m} are the electrodes distance and the membrane thickness respectively; k_{aq} and k_{m} are the conductivities of the solution and the membrane respectively, i_{mfc} is the current density of a single microbial fuel cell; η_{a} and η_{c} are the overpotentials of anodic and cathodic respectively, and can be calculated out by using the principles of the mass balances and the charge balance in the anode and cathode chambers respectively.

In the anode chamber, the mass balances of acetate, dissolved CO_2, hydrogen protons H^+ and biomass are expressed by

$$V_{\mathrm{a}} \frac{\mathrm{d}C_{\mathrm{AC}}}{\mathrm{d}t} = Q_{\mathrm{a}}(C_{\mathrm{AC}}^{\mathrm{in}} - C_{\mathrm{AC}}) - A_{\mathrm{m}} r_1 \quad (4)$$

$$V_{\mathrm{a}} \frac{\mathrm{d}C_{\mathrm{CO_2}}}{\mathrm{d}t} = Q_{\mathrm{a}}(C_{\mathrm{CO_2}}^{\mathrm{in}} - C_{\mathrm{CO_2}}) + 2A_{\mathrm{m}} r_1 \quad (5)$$

$$V_{\mathrm{a}} \frac{\mathrm{d}C_{\mathrm{H}}}{\mathrm{d}t} = Q_{\mathrm{a}}(C_{\mathrm{H}}^{\mathrm{in}} - C_{\mathrm{H}}) + 8A_{\mathrm{m}} r_1 \quad (6)$$

$$V_{\mathrm{a}} \frac{\mathrm{d}X}{\mathrm{d}t} = Q_{\mathrm{a}}\left(\frac{X^{\mathrm{in}} - X}{f_{\mathrm{x}}}\right) + A_{\mathrm{m}} Y_{\mathrm{ac}} r_1 - V_{\mathrm{a}} K_{\mathrm{dec}} X \quad (7)$$

The subscripts 'in' and 'a' in the above equations denote the flow of feed and the anode respectively, X and C_{AC} are the concentrations of biomass and acetate in the anode chamber respectively; V, A_{m} and Q are the chamber volume, the cross-section area of membrane and the feed flow rate respectively; f_{x}, Y_{ac} and K_{dec} are the reciprocal of the wash-out fraction, the bacterial yield and the decay constant for acetate utilisers respectively.

The reaction rate in the anode can be modelled by a Monod-type equation, which can be described as:

$$r_1 = k_1^0 \exp\left(\frac{\alpha F}{RT} \eta_{\mathrm{a}}\right) \frac{C_{\mathrm{AC}}}{K_{\mathrm{AC}} + C_{\mathrm{AC}}} X \quad (8)$$

where k_1^0 is the anode reaction rate constant at the condition of maximum specific growth rate, F is the Faraday constant, α is the anodic reaction charge transfer coefficient, K_{AC} is the half velocity rate constant for acetate, R is the gas constant, T is the microbial fuel cell operating temperature.

Furthermore, the charge balance at the anode is given by

$$C_{\mathrm{a}} \frac{\mathrm{d}\eta_a}{\mathrm{d}t} = 3600 i_{\mathrm{mfc}} - 8F r_1 \quad (9)$$

where C_{a} is the capacitance of the anode.

The mass balances in the cathode chamber are expressed by

$$V_{\mathrm{c}} \frac{\mathrm{d}C_{\mathrm{O_2}}}{\mathrm{d}t} = Q_{\mathrm{c}}(C_{\mathrm{O_2}}^{\mathrm{in}} - C_{\mathrm{O_2}}) + A_{\mathrm{m}} r_2 \quad (10)$$

$$V_{\mathrm{c}} \frac{\mathrm{d}C_{\mathrm{OH}}}{\mathrm{d}t} = Q_{\mathrm{a}}(C_{\mathrm{OH}}^{\mathrm{in}} - C_{\mathrm{OH}}) - 4A_{\mathrm{m}} r_2 \quad (11)$$

$$V_{\mathrm{c}} \frac{\mathrm{d}C_{\mathrm{M}}}{\mathrm{d}t} = Q_{\mathrm{c}}(C_{\mathrm{M}}^{\mathrm{in}} - C_{\mathrm{M}}) + A_{\mathrm{m}} N_{\mathrm{M}} \quad (12)$$

where the subscript 'c' denotes the cathode, $C_{\mathrm{O_2}}$ is the dissolved oxygen concentration in the cathode chamber, N_{M} is the flux of cation transported from anode to cathode via the membrane, and it can be calculated by

$$N_M = \frac{3600 i_{\mathrm{mfc}}}{F} \quad (13)$$

The reaction rate in the cathodic chamber can be incorporated to describe by a Butler–Volmer expression, and its expression can be written as:

$$r_2 = -k_2^0 \exp\left[(\beta - 1)\frac{F}{RT}\eta_C\right] \frac{C_{O_2}}{K_{O_2} + C_{O_2}} \quad (14)$$

where k_2^0 is the cathode reaction rate constant at the standard condition; K_{o2} is the half velocity rate constant for dissolved oxygen; β is the cathodic reaction charge transfer coefficient.

Furthermore, the charge balance at the cathode can be expressed by

$$C_{\mathrm{c}} \frac{\mathrm{d}\eta_{\mathrm{c}}}{\mathrm{d}t} = -3600 i_{\mathrm{mfc}} - 4F r_2 \quad (15)$$

where C_{c} is the capacitance of the cathode.

Thus the main processes of the microbial fuel cell are modeled. Based on the above described mathematical model, a Matlab/Simulink simulation model of a two-chamber microbial fuel cell can be set up, and it can be used to simulate the running states of a microbial fuel cell in various conditions.

Design an adaptive fuzzy control system

In order to keep the MFC system in a perfect functional mode, a suitable controller with the ability of efficient control is tightly related to the optimization of the performance of MFC system. Fuzzy control generally can maintain constant voltage output of the MFC system in a rigid condition. However, fuzzy control relies too much upon prior knowledge. And on the other hand, if control rule and parameters are fixed, fuzzy control may bring an undesirable phenomenon called steady-state error caused by non-adaptive ability of the controller when the operating conditions change in a wide range. So, for fitting in with the changing conditions, the fuzzy controller must be designed to have the ability of self-adapting. The structure of the closed-loop adaptive fuzzy control system is shown in fig. 1.

The control of PEMFC in this paper is aimed to keep the output voltage V_{mfc} equal to the given output voltage $\mathrm{V}_{\mathrm{mfc}}$. In order to obtain the satisfactory control effect, the error $e(k)$ and the change of error $ec(k)$ are used as the dual input of the main fuzzy controller. $e(k)$, $ec(k)$ and the control output $u(k)$ of the main fuzzy controller are given as:

$$e(k) = V_{\mathrm{mfc}}^{*} - V_{\mathrm{mfc}} \quad (16)$$

$$ec(k) = e(k) - e(k-1) \quad (17)$$

$$u(k) = u(k-1) + \mathrm{d}u(k) \quad (18)$$

Here d$u(k)$ is the inferred change of duty ratio by the main fuzzy controller.

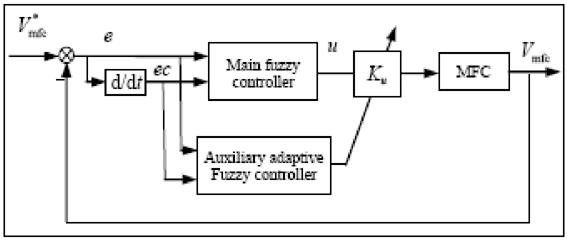

Fig. 1: Closed-loop adaptive fuzzy control system

For the main fuzzy controller, the error, the change of error and the change of output control variable choose the triangular type membership function. The fuzzy domain for *e*, *ec* is [-1, 1], and for d*u* is [0, 1]. The fuzzy set for *e* is {NB, NS, ZE, PS, PB}, and for *ec* and d*u* is {NB, NM, NS, ZE, PS, PM, PB}. The output control *u* of the main fuzzy controller is designed as Q_a, which is the input molar flow rate of fuel feed to anode. The fuzzy control rule base of the main fuzzy controller is shown in table 1.

For the purpose of reducing the steady-state error caused by the main fuzzy controller, an auxiliary adaptive fuzzy controller with dual inputs is designed to adjust the proportionality factor K_{u} of the main fuzzy controller. The inputs of the auxiliary adaptive fuzzy controller are still *e* and *ec*, the control output K_u of the auxiliary adaptive fuzzy controller is given as:

$$K_{\mathrm{u}}(k) = K_{\mathrm{u}}(k-1) + \mathrm{d}K_{\mathrm{u}}(k) \quad (19)$$

and d$K_u(k)$ is the inferred change of duty ratio by the auxiliary adaptive fuzzy controller.

The triangular type membership function is chosen for the change of the output control variable. The fuzzy domain for dK_u is [0,1]. The fuzzy set for dK_u is {NB, NM, NS, ZE, PS, PM, PB}. The output control K_{u} of the auxiliary adaptive fuzzy controller is designed as the value of proportionality factor in the main fuzzy controller. The fuzzy control rule base of the auxiliary adaptive fuzzy controller is shown in table 2.

SIMULATION AND RESULTS

To verify the control effect of the designed control scheme, simulations were done to compare the property of the system with that of fuzzy controller in Matlab/Simulink. The constants and the parameter values of experiment and model used in the simulation are shown in table 3.

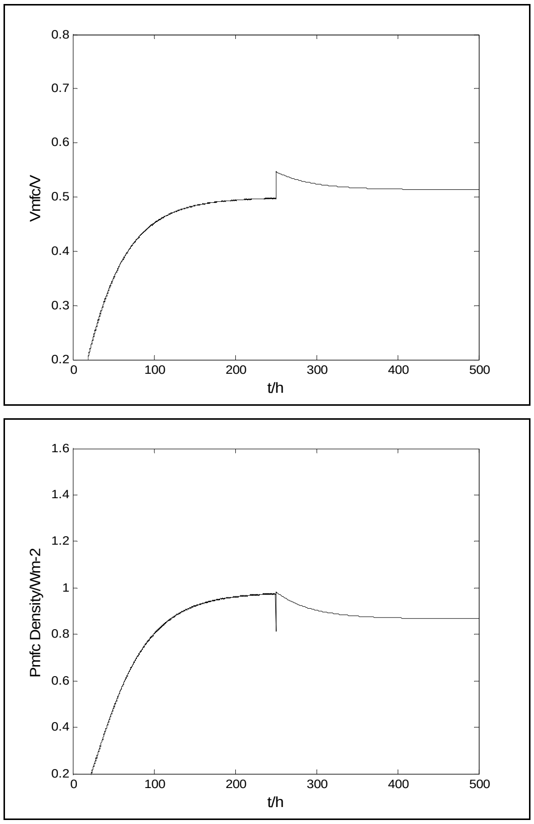

Fig. 2: Simulation results of uncontrolled MFC

The reference output voltage of the microbial fuel cell system is 0.5V. Aim to detect the ability of resisting disturbance, a test on fast load changes is executed. The load disturbance is brought by the external resistance fast changes from 500Ω to 600Ω at the time of 250h.

In the normal condition of no controller exists in its system, the output voltage of the microbial fuel cell system cannot maintain a constant value generally, and this can be seen from fig. 2. The output voltage of the MFC system without controller deviates from the reference setting steady value, and exists a steady-state error to accompany with slow response characteristic. Furthermore, when the external resistance changes from 500Ω to 600Ω at the time of 250h, the output voltage of the microbial fuel cell system undergoes an obvious undulation, and then attains stabilization with the steady-state error markedly after a long adjustment time.

In order to achieve the desired constant voltage output, the controllers are designed to adjust the input molar flow rate of fuel feed to anode. To corroborate the superiority of the adaptive fuzzy control method in the aspects of accuracy and response speed, simulation results of the adaptive fuzzy control are compared with the results of fuzzy control. For the fuzzy control scheme, the quantifying factors are K_{e}=1/2.25e-5, K_{ec}=0.001 and K_{u}=8.28e-5, and simulation results compared with fuzzy control with uncontrolled are shown in fig. 3.

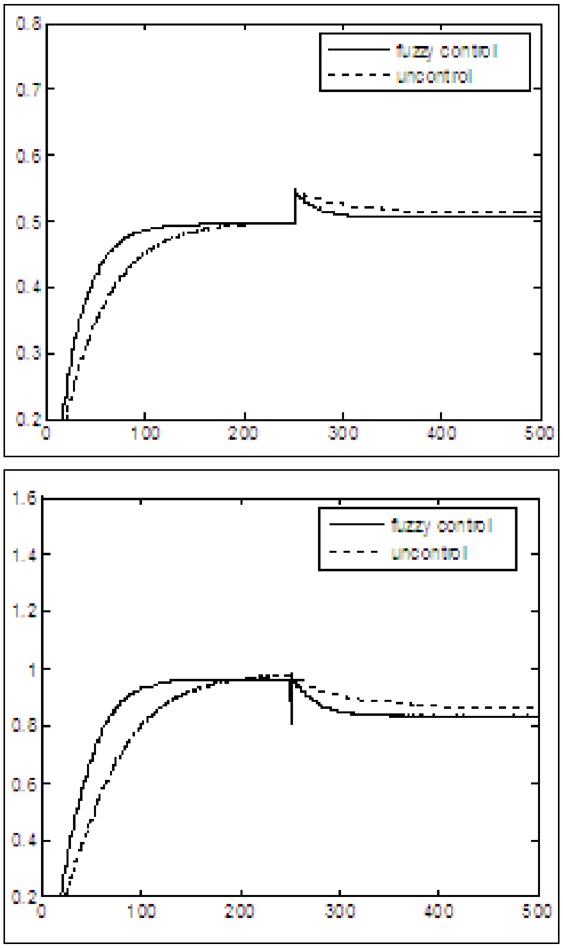

Fig. 3: Simulation results of MFC compared fuzzy control with uncontrolled

For the adaptive fuzzy control scheme, the quantifying factors of the main fuzzy controller are K_e=1/2.25e-5, K_{ec}=0.001, K_u is adjusted by the auxiliary adaptive fuzzy controller. The auxiliary adaptive fuzzy controller is designed as a variable coefficient fuzzy controller, and various quantifying factors are used according to the conditions of preliminary phase. Three phases of the auxiliary adaptive fuzzy controller are defined by human in allusion to the optimization of the controller. If the output voltage of MFC is less than 0.49, the preliminary phase is defined, and the quantifying factors of the auxiliary adaptive fuzzy controller are K_e=1/2.25e-5, K_{ec}=0.001 and K_u=1.7e-4. If the output voltage of MFC is greater than 0.5, the overshoot phase is defined, and the quantifying factors are K_e=1/2.25e-5, K_{ec}=0.001 and K_u=8.72e-4. If the voltage of MFC is between that of 0.49 and 0.5, the approach steady-state phase is defined, and the quantifying factors are K_e=1/2.25e-5, K_{ec}=0.001 and K_u=3.42e-4. Simulation results compared between adaptive fuzzy control with fuzzy control are shown in fig. 4.

From the controller design perspective, the control effect of a fuzzy controller is dependent on the integration of experiential knowledge of experts deeply. Aiming for improving the insufficient of the control effect of the fuzzy controller, the fuzzy coefficients ought to be adjusted by the other adaptive controller based on expertise. Adaptive fuzzy control designed in this paper can overcome the drawback of fuzzy control by using the auxiliary fuzzy controller to adjust the quantifying factor of the main fuzzy controller online on the basis of the alteration of the control phase objective. Meanwhile, the adaptive fuzzy control method combined self-adaption and feedback brings the faster time response, so the faster response characteristic can be integrated with the better steady-state behavior, and this can be seen from fig. 4. The output voltage of the MFC system shows less steady error and faster response speed. Adaptive fuzzy control can make the microbial fuel cell system track setting output voltage well.

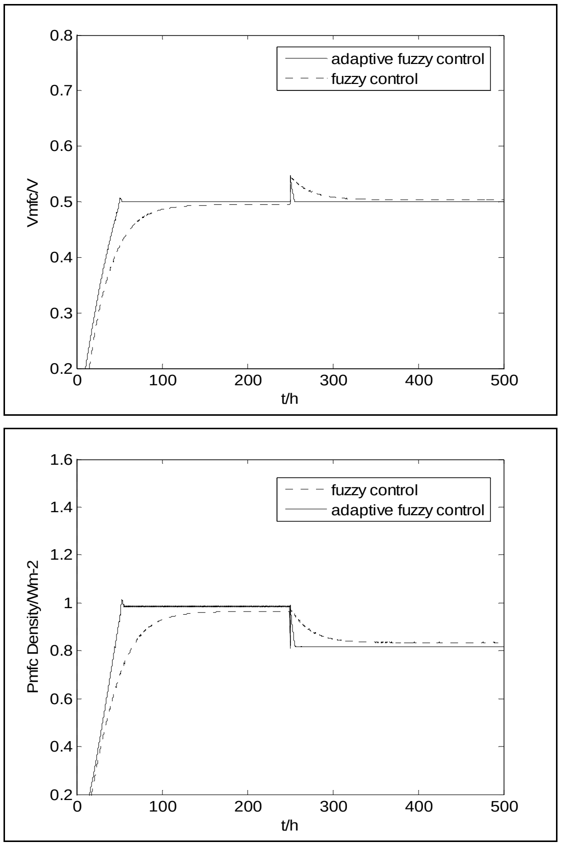

Fig. 4: Simulation results compared adaptive fuzzy control with fuzzy control

CONCLUSIONS

Microbial fuel cell systems are promising continuous alternative renewable electrical power sources. The adaptive fuzzy controller for the microbial fuel cell system devised in this paper can maintain the constant voltage output of MFC system even on the condition of fast load changes. The adaptive fuzzy controller has the ability of self-adapt the fuzzy parameters for strong robustness and insensitive to variations in external disturbances and is superior to fuzzy controller in steady-state behavior and response characteristic. The suitable control scheme can obtain desirable control

Table 1: Control rules of the main fuzzy controller

d*u*(*k*)		*ec*						
		NB	NM	NS	ZE	PS	PM	PB
e	NB	PB	PB	PB	PB	PM	PS	ZE
	NS	PB	PB	PM	PS	ZE	NS	NM
	ZE	PB	PM	PS	ZE	NS	NM	NB
	PS	PM	PS	ZE	NS	NM	NB	NB
	PB	ZE	NS	NM	NB	NB	NB	NB

Table 2: Control rules of the auxiliary fuzzy controller

dK_u		*ec*						
		NB	NM	NS	ZE	PS	PM	PB
e	NB	PB	PB	PB	PB	PB	PB	PB
	NM	PB	PB	PB	PM	PS	ZE	NS
	NS	PB	PM	PM	PS	ZE	NS	NM
	ZE	PB	PM	PS	ZE	NS	NM	NB
	PS	PM	PS	ZE	NS	NM	NM	NB
	PM	PS	ZE	NS	NM	NB	NB	NB
	PB	NB	NB	NB	NB	NB	NB	NB

Table 3: Parameter values of MFC model

Symbol	Description	Unit	Value
F	Faraday's constant	Coulombs mol^{-1}	96485.4
R	Gas constant	J mol^{-1}K^{-1}	8.3144
T	Temperature	K	303
k_{m}	Electrical conductivity of membrane	Ohm^{-1}m^{-1}	17
d_{m}	Thickness of membrane	m	1.778×10^{-4}
k_{aq}	Electrical conductivity of the aqueous solution	Ohm^{-1}m^{-1}	5
d_{mfc}	Distance between anode and cathode in the cell	m	0.022
C_{a}	Capacitance of anode	Fm^{-2}	400
C_{c}	Capacitance of cathode	Fm^{-2}	500
V_{a}	Volume of anode compartment	m^3	5.5×10^{-5}
V_{c}	Volume of cathode compartment	m^3	5.5×10^{-5}
A_{m}	Area of membrane	m^2	5×10^{-4}
Y_{ac}	Bacterial yield	Dimensionless	0.05
K_{dec}	Decay constant for acetate utilisers	h^{-1}	8.33×10^{-4}
f_{x}	Reciprocal of wash-out fraction	Dimensionless	10
Q_{a}	Flow rate of fuel feed to anode	m^{3}h^{-1}	2.25×10^{-5}
Q_{c}	Flow rate feeding to cathode compartment	m^{3}h^{-1}	1.11×10^{-3}
$C_{\mathrm{ac}}^{\mathrm{in}}$	Concentration of acetate in the influent of anode compartment	mol m^{-3}	1.56
$C_{\mathrm{co2}}^{\mathrm{in}}$	Concentration of CO_2 in the influent of anode compartment	mol m^{-3}	0
X_{in}	Concentration of bacteria in the influent of anode compartment	mol m^{-3}	0
$C_{\mathrm{H}}^{\mathrm{in}}$	Concentration of M^+ in the influent of anode compartment	mol m^{-3}	0
$C_{\mathrm{o2}}^{\mathrm{in}}$	Concentration of dissolved O_2 in the influent of cathode compartment	mol m^{-3}	0.3125
$C_{\mathrm{M}}^{\mathrm{in}}$	Concentration of M^+ in the influent of cathode compartment	mol m^{-3}	0
$C_{\mathrm{OH}}^{\mathrm{in}}$	Concentration of OH^- in the influent of cathode compartment	mol m^{-3}	0
V^0	Cell open circuit potential	V	0.770

effects in tracking a given voltage and make the microbial fuel cell system output a required constant voltage.

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