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Parametrized control-oriented mathematical model and adaptive backstepping control of a single chamber single population microbial fuel cell

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HIGHLIGHTS

- Control-Oriented Parametrized model for Microbial Fuel Cell is proposed.
- A novel adaptive backstepping control strategy is developed.
- Adaptive control strategy applied to single chamber single population MFC.
- Using dilution rate as input variable, substrate concentration is controlled.

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ABSTRACT

Microbial fuel cell (MFC) is a promising renewable energy technology wherein electrical power is obtained from the metabolism of microorganisms and simultaneous wastewater treatment. For efficient operation, MFCs need a control system for balance across fuel supply, mass, charge, and electrical load. Control-oriented models help in developing model based control strategies. Control-oriented parametrized model of single chamber single microorganism is presented in this paper. A backstepping and an adaptive backstepping control of a single chamber microbial fuel cell (MFC) with single microorganism kinetics, is presented. The key advantage of the backstepping scheme is its ability to handle systems with different relative degrees (difference between number of poles and zeros). In order to control the substrate concentration, the dilution rate of the MFC is used as a manipulated input variable. An adaptive action is provided for robustness to model uncertainties and online parameter estimation is performed. Lyapunov stability analysis ensures a convergent control scheme, and the control performances are illustrated using MATLAB/Simulink.

1. Introduction

In recent years, energy demands are rapidly increasing due to global industrialization and increased population growth. Such demands are mainly fulfilled by different energy sources such as fossil fuels, nuclear source and renewable sources [1]. Energy generated from fossil fuels like coal, natural gases etc. leads to negative impact on the environment such as atmospheric pollution and global warming. The development of renewable energy sources are required to balance such decrease of fossil fuel energy production [2].

In past few years, renewable energy technologies such as solar, wind, geothermal, biomass etc. have developed and significant research has been done. Power generated from the renewable energy sources is pure, efficient and eco-friendly [3]. Fuel cells (FC) and Microbial Fuel Cells (MFC) are also considered as promising renewable energy sources. A fuel cell is a device that converts chemical energy into a electrical energy. FCs have the highest efficiency compared to all sources and do not produce any polluting gases. MFCs are suitable devices that can be considered supplementary to FCs, and convert bio-chemical energy into electrical energy [4].

Microbial fuel cells (MFCs) are promising and challenging as a pollutant removal resource for sustainable energy generation. MFCs use microorganisms or bacterias as catalysts to oxidize substrate (organic and inorganic matters) and generate electricity. Water pollution is drastically increased due to industrial development and increased human population. There are many technologies developed for wastewater treatment which are inefficient, expensive or not sustainable [5]. Wastewater contains a variety of complex microbial communities like

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fermentative, methanogenic and anodophilic microorganisms. MFCs have the capability to generate electricity from wastewater and it is more advantageous compared to current wastewater treatment technologies due to increased conversion efficiency, the ability to produce bioelectricity, and operation at ambient temperature unlike the existing methods [6–8]. The performance of MFCs depend on the operational parameters such as growth rate of bacteria, temperature, pH value, influent substrate concentration, external resistance, etc. and the design parameters such as size and materials of the electrodes, electrode surface area, biofilm size, types of the electron donor, internal losses, types of the membrane etc. [9–12].

MFC technology is still at the laboratory level and is yet to be commercialized significantly which will need continued research. Mathematical models are required to obtain a relationship between parameters, inputs, outputs and system behavior. Few mathematical models of MFCs are developed and verified under certain assumptions and conditions. For optimal performance, the operation must be under controlled conditions, and so different control strategies are applied to MFCs. This paper presents control-oriented parametrized models for three different MFCs and develops an adaptive backstepping control scheme for single chamber single population MFC. Performance of the linear control techniques which have been previously developed for MFCs may be affected by unmodeled dynamics and parametric uncertainties. A nonlinear adaptive control technique provides better performance against unmodeled dynamics and parametric uncertainties. The proposed adaptive control technique provides robustness against parametric uncertainty within certain bounds and estimates the parameters on-line. The closed-loop system is evaluated by Lyapunov analysis and the performance of the adaptive backstepping control technique against parametric uncertainty is validated through simulation study.

2. Developments in mathematical modeling of MFCs

A mathematical model of the MFC converts the complex system into simple mathematical equations to evaluate the effect of design and operational parameters on the overall performance. Engineering-based models and statistical models are the two types of models used in MFCs. Engineering-based models are developed with ordinary differential equations (ODEs) and partial differential equations (PDEs) based on the impact of relevant parameters on the output performance. Modeling of MFCs have been developed based on different aspects such as number of microorganism cultures, modeling of anode and/or cathode chambers, modes of substrate supply and transfer of ions and electrons [13]. Equations used in mathematical modeling of MFCs are provided in Table 1.

In these formulae, μ and μ_{max} are specific bacterial growth and it's maximum value respectively, C_s and K_s are the substrate concentration and half-saturation constant respectively, E, E_{eq} and E^0 are electrode potential, equilibrium potential and standard electrode potential respectively, i and i_0 are the current density and exchange current density respectively, F, T and R are Faraday's constant, Temperature and universal gas constant respectively, α_a and α_c are the anode and cathode charge transfer coefficient, n is the no of electrons transferred, Q is the reaction quotient. Overview of MFCs models with their categorization are provided in Table 2.

Table 1
Equations used in physical and electrochemical modeling of MFCs [22].

Equation Name	Formula	Application in Models
Monod	$\mu = \mu_{max}\frac{C_s}{K_s + C_s}$	Bacterial growth and Substrate oxidation
Tafel	$E = E_{eq} + \frac{RT}{(1-\alpha)nF} ln\left(\frac{i}{i_0}\right)$	Electrode Kinetics
Nernst	$E = E_0 - \frac{RT}{(1-\alpha)nF} ln(Q)$	Electrochemical behavior
Butler-Volmer	$i = i_0\left[exp\left(\alpha_a \frac{nF}{RT}\left(E - E_{eq}\right)\right) - exp\left(-\alpha_c \frac{nF}{RT}\left(E - E_{eq}\right)\right)\right]$	Current Density

2.1. Single chamber single-population microbial fuel cell

Basic components of MFCs are anode, cathode, media (substrate), membrane and microorganisms. The basic construction of microbial fuel cell is shown in Fig. 1. Bacterias present in anode chamber generate protons and electrons by using substrates like acetate, glucose, lactate, nitrilotriacetic acid, ribitol, glucuronic acid, cysteine etc. [24]. Generated electrons are directly or indirectly transferred to the anode. Direct electron transfer happens through nanowires or intracellular mediator and biofilm produced at anode surface [25]. An external mediator is added to transfer electrons from bacteria to anode, called the indirect way to transfer electrons [26]. Generally, *Shewanella putrefaciens, G. Sulferredunces, G. Metallireducens, Rhodoferax ferrieducens, E. Coli, Sreptococcus lactis, Proteus vulgaris and Pseudomonas* bacterias are used in MFCs [3]. Electrons are transferred from anode to cathode via an external circuit. Protons are transferred from anode to cathode through proton exchange membrane (PEM). Electrons and protons combine at cathode, make fresh water and generate electricity from wastewater.

Ali Abul et al. developed single-chamber microbial fuel cell model with a proton exchange membrane. Acetate is the substrate and *G. sulfurreducens* is the bacterium. Some assumptions that were made, include: ideal substrate mixing during modeling, no addition of active biomass to the system, negligible substrate gradient in the biofilm, and constant system temperature [20]. The reactions in anode and cathode compartments are

$$CH_3COO^- + 4H_2O \rightarrow 2HCO_3^- + 9H^+ + 8e^-,$$

$$O_2 + 4H^+ + 4e^- \rightarrow 2H_2O.$$

2.1.1. Microbial kinetics

Monod equation gives the relationship between active biomass (the total quantity of organism) and substrate dynamics. Active biomass requires energy for maintenance (like re-synthesis, transport, osmotic regulation, heat loss etc.) which is caused by the flow of electron and energy through endogenous decay. The net biomass growth rate is the sum of synthesis and decay rates, and is given by

$$\mu = \left(\frac{1}{X}\frac{dX}{dt}\right)_{syn} + \left(\frac{1}{X}\frac{dX}{dt}\right)_{dec} = \mu_{syn} + \mu_{dec} = \mu_{max}\frac{C_s}{k_s + C_s} - K_d,$$

where μ_{syn} and μ_{max} are specific growth rate and maximum specific growth rate of microorganisms respectively, X is the biomass concentration, C_s is the substrate concentration, K_s is the half saturation constant, $K_d > 0$ is the decay coefficient.

Bacteria breaks down the substrate and utilizes it to live and grow. The cell growth is derived from the substrate utilization given by

$$q = q_{max}\frac{C_s}{K_s + C_s}X, \tag{1}$$

where q is the rate of substrate utilization and q_{max} is the maximum rate of the same.

2.1.2. Physical model

Microbial fuel cell system receives a feed flow at the anode with a rate of Q_a in terms of substrate concentration C_{so} and modulates the MFC behavior. The rate of change in substrate concentration and represented by the net rate of cell growth are respectively

$$\frac{dC_s}{dt} = -qX + D(C_{so} - C_s), \tag{2}$$