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Review

Biofuel cells and their development

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Abstract

This review considers the literature published since 1994 on microbial and enzymatic biofuel cells. Types of biofuel cell are classified according to the nature of the electrode reaction and the nature of the biochemical reactions. The performance of fuel cells is critically reviewed and a variety of possible applications is considered. The current direction of development of biofuel cells is carefully analysed. While considerable chemical development of enzyme electrodes has occurred, relatively little progress has been made towards the engineering development biofuel cells. The limit of performance of biofuel cells is highlighted and suggestions for future research directions are provided.

Keywords: Biofuel cell; Enzymatic fuel cell; Microbial fuel cell; Enzyme electrode

Contents

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Nomenclature

A	geometric area of electrode (cm^2)
A_e	area of electrode per unit volume ($cm^2\ cm^{-3}$)
c_i	concentration of species i ($mol\ dm^{-3}$)
E	electrode potential versus a reference electrode (V)
E_{cell}	cell potential (V)
E_e	equilibrium potential (V)
F	Faraday constant ($C\ mol^{-1}$)
I	current (A)
j	current density ($A\ cm^{-2}$)
k	rate constant for a chemical reaction (first order s^{-1}, etc.)
k_{max}	maximum rate constant for an enzyme reaction (first order s^{-1}, etc.)
K_m	Michaelis–Menten constant (mol)
m	mass (g or kg)
P_{cell}	power output of cell (W)
R	molar gas constant ($J\ K^{-1}\ mol^{-1}$)
R_e	resistance (Ω)
t	time (s)
T	temperature (K)
V_e	electrode volume (cm^3)
z	number of electrons involved in electrode reactions

Greek symbol

η	overpotential, $=E - E_e$ (V)

Subscripts

A	anode
C	cathode
O	oxidised species
R	reduced species

1. Introduction

Biological fuel cells (biofuel cells) have been defined as fuel cells that rely on enzymatic catalysis for at least part of their activity (Palmore and Whitesides, 1994). A broader definition would consider biofuel cells as those fuel cells which use biocatalysts, which includes systems utilising non-enzyme proteins as well. In the broadest sense, we would define biological fuel cells are devices capable of directly transforming chemical to electrical energy via electrochemical reactions involving biochemical pathways.

The connection between biology and electricity has been known since the experiments of Galvani in the 1780s (Galvani, 1791), when it was discovered that current from a static electricity generator could cause a severed frog's leg to twitch, revolutionising the understanding of the nervous system. The fuel cell has been known for almost as long, since Grove successfully reversed the action of the electrolysis of water, recombining hydrogen and oxygen to produce water and electrical current (Grove, 1839). Given the early nature of these two discoveries it is perhaps surprising that a half cell using microorganisms was not demonstrated until 1910, when M.C. Potter, a professor of Botany at the University of Durham observed electricity production by *E. coli* (Potter, 1910). These results were not widely reported until the experiments of Cohen in 1931 who demonstrated a voltage greater than 35 V from microbial fuel cells connected in electrical series (Cohen, 1931).

The expansion of interest in fuel cells triggered by the USA space program, in the late 1950s and early 1960s, led to the development of microbial biofuel cells as a possible technology for a waste disposal system for space flights that would also generate power. Also in the late 1960s, the biofuel cell using cell-free enzyme systems began to be used, with the early goal of a power supply for a permanently implantable artificial heart (Kreysa et al., 1990; Wingard et al., 1982) and references within).

In a fuel cell, an oxidation reaction occurs at the anode and a reduction reaction at the cathode. The oxidation releases electrons, which travel to the cathode via the external circuit doing electrical work. The circuit is completed by the movement of a compensating charge through the electrolyte often in the form of positive ions.

Conventionally, fuel cells operate using relatively simple inorganic chemistries, taking such fuels as hydrogen or methanol (MeOH), and producing energy, water and carbon dioxide (in the case of methanol). Other fuels, such as other lower order alcohols and alkanes, are also used, but they are frequently reformed to produce hydrogen before the fuel cell process (Mitsos et al., 2004; Vielstich et al., 2003).

Conventional fuel cells are regarded as 'low temperature' if they operate in the region of 80 °C and typically require expensive p-group catalysts (Larminie and Dicks, 2000). A summary of the main types of inorganic fuel cell is presented in Table 1.

Biofuel cells use enzymes as catalysts (alone or within an organism) and tend operate under mild conditions (20–40 °C,

Table 1
Inorganic fuel cell properties (after Larminie and Dicks, 2000)

Type of fuel cell	Mobile ion	Operating temperature (°C)	Application
Alkaline (AFC)	OH^-	50–200	Used in NASA space vehicles, e.g. Apollo, shuttle
Proton exchange membrane (PEMFC)	H^+	50–100	Especially suitable for vehicles and mobile applications but also for low power CHP systems
Phosphoric acid (PAFC)	H^+	≈220	Large numbers of 200 kW CHP systems in use
Molten carbonate (MCFC)	CO_3^{2-}	≈650	Suitable for medium to large scale CHP systems up to MW capacity
Solid oxide (SOFC)	O^{2-}	500–1000	Suitable for all sizes of CHP systems, 2 kW to multi-MW