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The applications and prospect of fuel cells in medical field: A review

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ABSTRACT

Fuel cells directly convert chemical energy stored in fuels into electrical energy through electrochemical reactions and have been identified as one of the most promising technologies for the clean energy industry of the future. In recent years, fuel cells have been applied in the medical field in both exploratory research and prospective products, as they offer multiple advantages over conventional batteries, including ease of recharging, environmentally friendly character and high security. In this paper, we summarize the up to date progress of this energy system in implantable medical devices which use microorganisms, enzymes and precious metals as catalysts, respectively. Safety is the most concerned issue in this application. In addition, we introduce a variety of applications of fuel cells on the vitro medical equipments (such as blood glucose meter, alcohol tester, wound treatment instrument). The introduction of fuel cells on implementable medical devices is in early stage of research, nonetheless the prospects/potential of this application are grant. Evidently, mankind could come across a new medical revolution upon the successful introduction of fuel cells to the human body.

Contents

1. Introduction

Facing the challenge of the global environment and the energy today, people would be confident of the future world with the rapidly developing new energy technologies. As an indispensable part of these technologies, fuel cells have received strong support from mainly several developed countries including U.S.A, Japan, Korea and U.K. According to fuel cell market survey report by U.S Energy Department, fuel cell market will increase to about $2.54 billion in 2018 by $630 million in 2013, highlighting the increasing interest and prospect of this energy system [1].

The history of fuel cell is an uneven road, from its proposal by British chemist David in 1839 to today [2]. In 1911, Pottet's anaerobic experiments with yeast and coli resulted in weak current obtained in a metal foil electrode [3]. The above finding led to the introduction of a new field with the microbial fuel cell as the main research topic. Yet, the research stagnated in the following decades until 1952 with the introduction of the “Bacon battery” [4].

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Meanwhile, the development of space technology initiated scientists to invent ways to transform organic waste generated during the space flight into available electrical power [5].

In 1964, Yahiro proposed fuel cells as a power supply for implantable medical devices [6]. At that time, the majority of the fuel cell studies focused on the use of glucose and oxygen as reactants and biological enzyme as the catalyst [7]. Still, fuel cell research in medical field went temporarily into the trough due to the successful integration of lithium battery in this filed. In 1973, the oil crisis shifted the interest of industry and research to alternative energy systems including fuel cells. Since then, this energy system ushered in a broad prospect [8]. In 1980 s, redox mediator was widely used in the biofuel cell, which can be applied as a small power supply [9,10].

A fuel cell generally refers to the device which transforms the chemical energy stored in the fuel into the electrical energy directly by an electrochemical reaction. It is composed of an anode, a cathode and the electrolyte [11]. Fuel is oxidized on the anode, releasing protons and electrons. The protons are transported through the electrolyte to the cathode. The electrons flow to the cathode through an external circuit under the electrical potential. Depending on the electrolyte, several different types can be defined, such as hydrogen-oxygen proton exchange membrane fuel cells (PEMFC), direct methanol fuel cell (DMFC), solid oxide fuel cell (SOFC), alkaline fuel cell (AFC), molten carbonate fuel cell (MCFC), and phosphoric acid fuel cell (PAFC) [12].

When compared with conventional batteries and internal combustion engines, fuel cells hold many significant advantages [13]. First, the energy conversion efficiency can reach more than 50%. The energy efficiency can be modulated by introducing a) multiple single cells to obtain set power output; and b) wide fuel sources such as hydrogen, methanol, ethanol, as well as natural gas as fuel. Furthermore, noise is not an issue here as this system consists of few moving parts. On top of the above, fuel cell can reduce harmful gas emissions, such that it is environment-friendly. On the other side, there are still critical issues that need to be resolved before the successful commercialization, such as the relatively high operating and capital costs as well as cyclability and durability. Moreover, it is difficult to produce, transport and store hydrogen [13].

The application field of fuel cells is vast [14]. Currently, large fuel cells are indispensable in stationary power industry such as the residence, commerce and industry. About 70% of the fuel cell market is used in stationary power generation [15]. In addition, the miniaturization of fuel cells to be integrated in portable electronic devices is currently heavily studied by both industry and institutes [16], focusing on consumer electronics devices market such as mobile phones [17,18]. Fuel cell is an ideal choice for the substitute of internal combustion engine in the future. At present, development priorities of fuel cell is in various transportation vehicles especially in light buses. Fuel cell vehicles (FCV) have been commercialized in 2015 with Toyota releasing the world's first mass-produced fuel cell vehicle MIRAI [19]. Fuel cell has become a new competitor as a back-up power in the market for telecommunications networks [20], material handling [21,22] and airport ground support equipments [23].

In recent years, researches of fuel cells have intensified on other fields apart from energy including the medical field [24]. Preliminary studies have demonstrated constructive results, bringing the gospel to countless patients. In this paper, in line with different aspects in medical field, the applications of fuel cell are divided into implantable medical devices and non-implantable medical devices, both are elaborated systematically.

2. Applications of fuel cell in implantable medical devices

Implantable medical devices (IMDs) can be divided into two categories, i.e. functional assisted devices [25] and in-vivo measurements devices [26]. The former includes pacemakers [27], cochlear implants [28], drug pumps [29] and biochips [30] while the latter includes blood counter, blood glucose meters [31] and temperature sensors. The common feature of IMDs is that they require stable and efficient power [32]. Traditional implantable medical devices are powered by lithium-ion batteries that need to be replaced from time to time. This replacement process leads to high medical costs and causes intolerable pain to the patients. Fuel cell exhibits high energy conversion efficiency, mild operation conditions, simple structure and the most importantly, excellent biocompatibility and long lifetime without refueling from time to time, since the organic compounds and oxygen inside the human body can be used as fuel and oxidant. Integrating fuel cells to in vivo implantable devices (as the implantable medical device power or implantable medical sensor) will largely reduce the medical costs and alleviate the pain of patients. Current research on fuel cells used in implantable medical devices is mainly concentrated on employing microorganism, biological enzyme and precious metals as catalysts. Using microbial tissue inside human body as catalyst is the most attractive prospect for the fuel cell powering the implantable medical devices due to the easy setting-up and low cost, but the intense selectivity of the kind of microorganism and the poor output power limit its wide application. On the other hand, applying enzyme as catalyst shows excellent compatibility and considerable power, but it suffers from short duration of enzyme such that the rapid degradation of fuel cell performance. Using precious metal as catalyst of fuel cell can lead to high power and long-term stable performance, however, the toxicity of such catalyst to the living body has not been clarified and the cost of the implantable medical devices will be largely increased. Developing catalysts with good biocompatibility, stable performance as well as low cost for the fuel cell used in implantable medical devices is still an on-going endeavor.

2.1. Applying microorganism as catalysts

The earliest application of fuel cell in medical field is the microbial fuel cell (MFC) [33]. Microbial tissue was applied as catalyst. Justin et al. [34–36] obtained electrical energy by a MFC containing Escherichia coli and human white blood cells. The results showed that the voltage and current were related to the ability of oxidation of glucose by Escherichia coli. In another experiment using human white blood cells as catalyst, the generated current was smaller than the recorded value from Escherichia coli catalyst. Their research shows the possibility of using human cells and fluids to generate power for implantable medical devices in the future.

Taking into account the symbiotic relationship between human beings and microorganisms, Liu et al. [37,38] reported a microbial fuel cell set-up in the transverse colon of the body. The anode, made of biocompatible material was helically attached to the inner wall of the intestine. The cathode was arranged at the middle part of the intestine where high concentration oxygen is present. Through such positioning, the cell can continuously and steadily generate electricity as a result of intestinal motility of the microorganisms and intestine contents. This system revolutionized the concept and prospect of implantable medical devices, showing a radically new approach to supply power for them. Han et al. proposed to utilize a MFC implanted in the human colon [39]. Because of the large number of anaerobic microorganisms naturally present in the intestinal mucosa and, at the same time, many aerobic microorganisms in the lumen flowing with feces mass, the