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# Harvesting of PEM fuel cell heat energy for a thermal engine in an underwater glider

Shuxin Wang [a,*], Chungang Xie [a], Yanhui Wang [a], Lianhong Zhang [a], Weiping Jie [a], S. Jack Hu [b]

[a] *School of Mechanical Engineering, Tianjin University, Tianjin 300072, China*
[b] *Department of Mechanical Engineering, The University of Michigan, Ann Arbor, MI 48109-2125, USA*

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**Abstract**

The heat generated by a proton exchange membrane fuel cell (PEMFC) is generally removed from the cell by a cooling system. Combining heat energy and electricity in a PEMFC is highly desirable to achieve higher fuel efficiency. This paper describes the design of a new power system that combines the heat energy and electricity in a miniature PEMFC to improve the overall power efficiency in an underwater glider. The system makes use of the available heat energy for navigational power of the underwater glider while the electricity generated by the miniature PEMFC is used for the glider's sensors and control system. Experimental results show that the performance of the thermal engine can be obviously improved due to the high quality heat from the PEMFC compared with the ocean environmental thermal energy. Moreover, the overall fuel efficiency can be increased from 17 to 25% at different electric power levels by harvesting the PEMFC heat energy for an integrated fuel cell and thermal engine system in the underwater glider.


*Keywords:* Energy harvesting; Miniature PEMFC; Underwater glider; Thermal engine

## 1. Introduction

Proton exchange membrane fuel cells (PEMFC) produce heat in the process of generating electricity due to the irreversible electrochemical reactions and polarizations. This heat is usually 40–60% of the total chemical energy which is generally viewed as waste heat and expelled from the cell for the sake of safety and stability [1,2]. For high temperature fuel cells such as molten carbonate fuel cells (MCFC) and solid oxide fuel cells (SOFC), or large-scale PEMFC and phosphoric acid fuel cells (PAFC), the heat energy can be recycled to improve the fuel efficiency by generating electricity or utilizing heat directly [3–7]. However, for a miniature PEMFC, the low temperature (about 60 °C) and the limited amount of heat make recycling of reaction heat difficult. A power system design that uses both the electricity of the miniature PEMFC and the heat energy would not only resolve the problem of thermal management, but also improve the fuel efficiency. This paper describes a power system for an underwater glider that makes use of reaction heat of the PEMFC as the inner heat source of the thermal engine so as to realize the integration of heat and electricity for the fuel cell, while the miniature PEMFC produces electricity for the sensors and control system of the glider. In this way, the thermal engine can convert the heat from the PEMFC into pressure energy, which is utilized to change the buoyancy of the glider in order to ascend form deep sea to surface. Laboratory experiments show that this new power system should be available for the needs of thermal and electrical loads in the glider and the heat-to-power (electricity) ratio of the PEMFC can be effectively altered under a variety of operating conditions beside the resistance heaters to satisfy the requirement of different navigational performance. Moreover, the overall power efficiency of the underwater glider can be greatly improved by the harvesting the PEMFC heat energy for the thermal engine application.

* Corresponding author. Tel.: +86 22 27403434; fax: +86 22 87402173.
*E-mail address:* shuxinw@tju.edu.cn (S. Wang).

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## 2. Background

### 2.1. Fuel cell

A fuel cell is a device that directly converts chemical energy into electrical and thermal energy under isothermal conditions by consuming hydrogen-rich fuel and oxidant [8]. In the PEMFC, hydrogen flowing along a gas channel at the anode is mostly ionized into hydrogen ions under the action of a catalyst where electrochemical reactions take place. Hydrogen and oxygen are rigorously separated by a membrane through which hydrogen ions can easily pass while electrons travel around the external circuit from the anode to the cathode producing useful electrical energy. At the cathode, oxygen combines hydrogen ions and electrons into water with heat as a by-product. Electrochemical reactions for the anode and cathode are shown in Fig. 1 for a hydrogen–oxygen PEMFC.The total reaction is characterized as:

$$H_2 + O_2 \rightarrow H_2O\,(l) + \Delta H \qquad (1)$$

where $\Delta H$ is the enthalpy change due to the electrochemical reaction of hydrogen and oxygen in a PEMFC. The total chemical energy that is released by the reaction is divided into electrical and thermal components. In practice, the total chemical energy is never completely utilized because of thermodynamic irreversibility including heat transfer, friction, mixing, chemical reaction and different polarizations [9]. Theoretically, the maximum PEMFC efficiency $\eta_{max}$ can be determined as follows [10]:

$$\eta_{max} = \frac{\Delta G}{\Delta H} = 1 - \frac{T\,\Delta S}{\Delta H} \qquad (2)$$

where $\Delta G$ is the Gibbs free energy change which describes the maximum energy including both electricity and heat, $T\,\Delta S$ is the irreversible entropy change due to thermodynamic irreversibility. Thermodynamic irreversibility results in lower voltage and lower fuel efficiency because the heat produced must be removed from the cell to prevent the membrane from dehydration and overheating. Therefore, thermal management is an important issue for PEMFC safety and stability. Waste heat should be properly managed with cooling channels in the stack, where the coolant cycles and carries waste heat to the heat exchanger continuously in order to maintain the isothermal condition for the PEMFC.

### 2.2. Underwater glider and thermal engine

As an underwater vehicle, an autonomous underwater glider can take a variety of sensors to perform long-duration measurements. The glider takes in and expels water to change its buoyancy to cycle vertically in the ocean and uses small wings in cooperation with the position adjustment of center of gravity to convert this vertical velocity into forward motion [11]. Underwater gliders can be divided into electric gliders and thermal gliders depending on the power sources they use [12,13]. Figs. 2a and 2b show the typical electric and thermal gliders respectively.

Electric gliders powered by electrical buoyancy engines have proven to be very reliable through many sea experiments. However, the battery capacity (lithium or alkaline batteries) limits the duration and range of navigation. Moreover, electric gliders with large operating depths usually adopt reciprocating pumps as buoyancy engines. The reciprocating pump is sensitive to "vapor lock" while it pressurizes the working fluid into the external bladder in order to increase the buoyancy of the glider. Sometimes the work fluid cannot be pressurized at all, because a pump cylinder filled with gas released from the work fluid has an insufficient compression ratio for the pump [11].

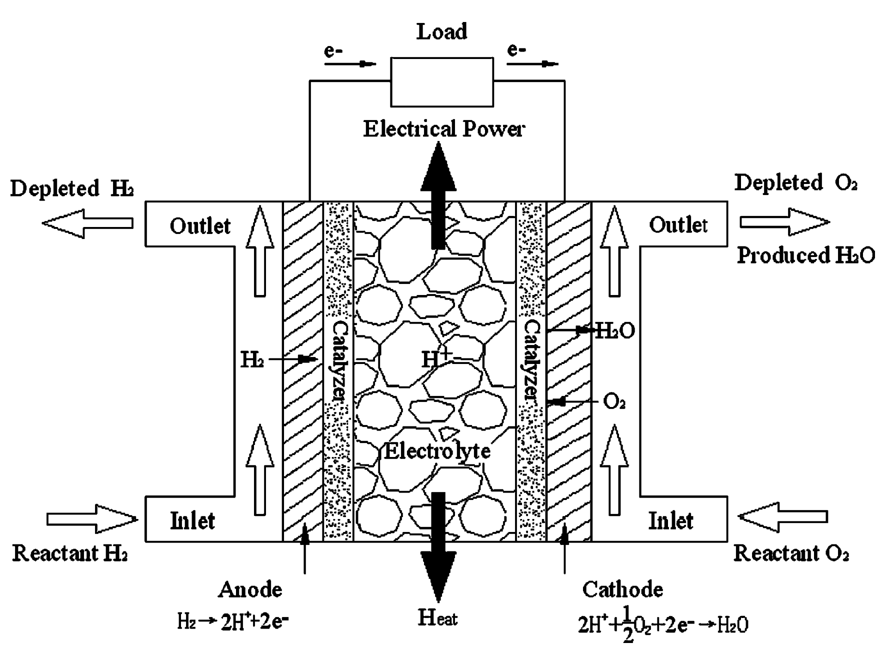


Fig. 1. Electrochemical reactions in a hydrogen–oxygen PEMFC.