Proton Exchange Membrane Fuel Cell Technology Status and Applicability for Propulsion of Autonomous Underwater Vehicles

F. Barbir
Proton Energy Systems
50 Inwood Road
Rocky Hill, CT 06067

Abstract – **Proton Exchange Membrane (PEM) fuel cells are being developed for propulsion of automobiles and for portable and stationary power generation. This paper reviews the technology status in terms of performance, durability, size and weight. An example of a closed loop system is described together with its operational characteristics. Various hydrogen/oxygen storage and refueling options are discussed. The PEM fuel cells may be attractive for propulsion of underwater vehicles because of high efficiency, quiet operation, low thermal signature, neutral buoyancy, and dept independence of the process.**

I. Introduction

Although the first application of Proton Exchange Membrane (PEM) fuel cells was in the space program in 1960's, this technology is currently on its way to be commercialized for automotive and stationary power applications. Because of their simplicity and power density the Proton Exchange Membrane (PEM) fuel cells seem to be an attractive option for propulsion of automobiles. In addition, the fuel cells offer better efficiency and lower emissions. Almost every car manufacturer has already demonstrated a fuel cell powered vehicle, and announced plans for production. Some have already gone through several generations of prototypes. One of the major obstacles for public acceptance and commercialization of fuel cell vehicles is difficulty of storing or producing hydrogen on-board. This is less of a problem for the fuel cell powered buses since there is enough space to put hydrogen storage on the roof of the vehicle, which also proves to be a safe option. Application of fuel cells as an auxiliary power unit in passenger vehicles and especially in trucks has also been explored.

In stationary power generation the fuel cells offer not only better efficiency and lower emissions, but also a tremendous flexibility. Their power output ranges from less than a kW to several hundreds of kilowatts. PEM fuel cells are limited to applications up to 250 kW, while the high temperature fuel cells (molten carbonate and solid oxide) are being developed with power outputs up to several MW. Stationary fuel cells are ideal for distributed generation, since they may be installed at almost any location. Stationary fuel cells may also be used for cogeneration of power and heat. Small fuel cells (1-5 kW) are being developed for residential applications. The fuel of choice for residential fuel cells is typically natural gas, although some attempts have been made to use propane or methanol.

Fuel cells are also being developed for back-up power, or uninterruptible power applications, primarily for tele-communications and computer systems. It appears that the fuel cell systems have an advantage over batteries currently being used for this application when energy storage needs exceed 5 kWh. The fuel may be natural gas or propane in which case these units must be equipped with a fuel processor. A better option is a regenerative fuel cell, i.e., a fuel cell equipped with an electrolyzer that generates hydrogen while the power from the grid is available. Hydrogen is then stored and used in the fuel cell to generate electricity when the grid is down.

Development of micro-fuel cells as replacement for the batteries for the cell phones and camcorders is also nearing commercialization. These fuel cells running on methanol offer longer operation and autonomy.

II. Technology Status

A. Power output

PEM fuel cell stacks and systems have been built with a power output ranging from several watts to 250 kW, which should satisfy the requirements of AUVs. A desired power output may be matched with a single stack or with several stacks connected in series or parallel depending on the desired voltage.

B. Efficiency

The efficiency of a fuel cell stack is directly proportional to its cell potential, which is a function of current density, i.e., power output. The fuel cell stack can be sized to rich its nominal power output at any cell potential between open circuit potential and the potential corresponding to maximum power density. A higher nominal cell voltage results in higher efficiency at nominal power, but also in larger required active area, therefore in a larger stack. In early prototypes the stacks were rated at or below 0.6 V/cell, but the requirement for higher efficiency in both automotive and stationary applications has pushed the nominal cell voltage to 0.7 V/cell or higher. In applications where the efficiency is more important than the size of the stack the nominal cell voltage may be selected at 0.8 V/cell or even higher. Propulsion of underwater vehicles is such application, since the fuel cell efficiency is directly related to the size of hydrogen and oxygen storage, which, depending on the duration of air independent operation may be significantly larger than the size of the fuel cell itself.

The efficiency of a fuel cell stack is:

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$$\eta_{FC} = \eta_I \cdot \eta_V = \frac{I}{I + I_{loss}} \frac{V_{cell}}{1.254} = \frac{1}{1+\varphi} \frac{V_{cell}}{1.254} \quad (1)$$

where:
η_{FC} = fuel cell stack efficiency (based on hydrogen's lower heating value),
η_I = current (Faradic) efficiency,
η_V = voltage efficiency,
I = stack current (A),
I_{loss} = internal (in stack) current losses due to internal currents and hydrogen/oxygen crossover (A),
V_{cell} = individual cell voltage (V) = stack voltage divided by the number of cells in the stack
1.254 = voltage corresponding to the hydrogen's lower heating value, and
$\varphi = I/I_{loss} = i/i_{loss}$, where i is the current density in A/cm^2; i_{loss} depends on the membrane thickness, operating pressure and cell construction, but typically is less than 2 mA/cm^2, therefore having an impact on stack efficiency only at extremely low current densities.

The efficiency of the fuel cell system must take into account the parasitic losses, i.e., power needed to run the ancillary components such as pumps, fans, solenoid valves, controls and instrumentation, as well as any power conversion losses. The fuel cell produces direct current at variable voltage. A DC/DC power conversion may be required for parasitic power, typically operating at 24 V or 48 V. Net power output of the fuel cell system also must be conditioned (DC/DC or DC/AC) depending on the type of load. In some cases the parasitics may also use AC. The system efficiency is therefore:

$$\eta_{sys} = \eta_{PCl}\left(1 - \frac{\xi}{\eta_{PCa}}\right)\eta_{FC} \quad (2a)$$

for the system with two power conditioners (i.e., one for ancillary components and one for the main load), or

$$\eta_{sys} = (\eta_{PCl} - \xi)\eta_{FC} \quad (2b)$$

for the system where the ancillary components operate at same voltage as the main load, and therefore a single power conditioner is used.

In the above equations:
η_{sys} = total electrical efficiency of the system (based on hydrogen's lower heating value)
η_{PCl} = efficiency of power conversion (DC/DC or DC/AC) for the main load
η_{PCa} = efficiency of power conversion (DC/DC) for the ancillary components
ξ = ratio of parasitic power and fuel cell stack gross power output; this ratio depends on system design and operating conditions, primarily operating pressure in hydrogen/air systems. In a well designed system, and particularly in hydrogen/oxygen systems this ratio should be less than 0.1.

The above efficiency definitions apply only to hydrogen systems which operate with 100% hydrogen utilization. The efficiency of the systems with fuel processor must be multiplied by the efficiency of the fuel processor and by the fuel utilization in the fuel cell stack. The efficiency of these systems is therefore significantly lower than the efficiency of the hydrogen systems. Assuming the efficiency of power conversion of 90% and ξ = 0.1, the efficiency of the hydrogen fuel cell system is a function of cell potential, V_{cell}, only. At 0.7 V/cell the system efficiency is 0.56, but for the cell potentials above 0.8 V the efficiency is higher than 0.64. The efficiency of the systems with fuel processors operating with air as oxidant is typically between 0.30 and 0.40 (higher end achievable only with the larger systems).

Hydrogen consumption is inversely proportional to the efficiency:

$$SFC = \frac{1}{\eta_{sys} \cdot \Delta H_{LHV}} \quad (3)$$

where:
SFC = specific fuel consumption in kg/kWh
ΔH_{LHV} = hydrogen lower heating value = 33.3 kWh/kg

The efficiency of 0. 6 therefore corresponds to hydrogen consumption of 0.05 kg/kWh.

C. Cell Voltage and Current Density – Polarization Curve

The size of the fuel cell stack depends on the current density achievable at selected nominal cell potential. Hydrogen/air stacks developed for automotive applications can reach current densities well above 1 A/cm^2 at 0.6 V/cell (or above 0.7 A/cm^2 at 0.7 V/cell). These stacks are typically operated pressurized at about 300 kPa. The stacks operated at ambient pressure reach lower current densities, typically above 0.7 A/cm^2 at 0.6 V/cell. Use of pure oxygen instead of air results in voltage gain, theoretically (due to Nernst equation) about 40-50 mV, but in practice this gain may be even higher (due to improved oxygen diffusion, not taken into account with Nernst equation). Figure 1 shows typical polarization curves of the hydrogen/air and hydrogen oxygen fuel cells. It should be mentioned that the hydrogen/oxygen fuel cell stack may use thicker membranes than comparable hydrogen/air stacks (for safety/reliability/durability reasons), resulting in some voltage loss due to ionic resistance. Since in hydrogen/oxygen systems both hydrogen and oxygen are typically available pressurized it is advantageous to operate the fuel cell at elevated pressure. Such operation results in voltage gain (again due to Nernst equation) without penalty in parasitic power for pressurization.

At 0.6 V/cell and 1 A/cm^2 the power density is 0.6 W/cm^2 (or 6 kW/m^2). Power densities of up to 1 W/cm^2 have been reported on a cell level, and with hydrogen/oxygen stacks/systems should be achievable at the stack level. However, at 0.8 V/cell the achievable power density is only about 0.3 W/cm^2.

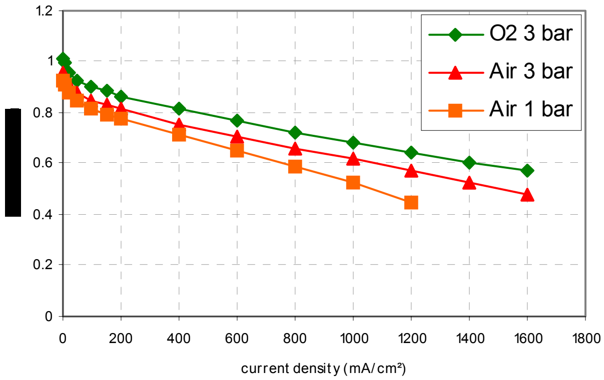

Fig. 1. Typical PEM polarization curves

D. Size and Weight

Stack size and weight depend on stack construction, particularly cell pitch (number of cells per inch or cm), active area, perimeter area, materials used, etc. A well designed stack should have less than 6 liters/m^2, and should weigh less than 10 kg/m^2 (where m^2 refers to the total active area inside the stack, i.e., cell active area times number of cells in the stack). This allows achieving stack power densities higher then 1 kW/kg and 1.5 kW/lit, which have been reported in automotive applications.

The complete system may be several times the size and the weight of the fuel cell stack itself. The goals of the DoE fuel cells for transportation program are 3.3 kg/kW and 3.3 l/kW.

E. Durability

Durability of PEM fuel cells is an important parameter, although requirements differ between various applications. For example, the requirement for automotive applications is 5,000 operating hours, but for buses and delivery vehicles it is significantly higher. The requirement for stationary applications is at least 40,000 operating hours, but preferably 80,000 hours. The PEM fuel cells at the current stage of development cannot meet these requirements. The causes of PEM fuel cell performance degradation and eventually failure are not well understood. It may be caused by the morphological changes in polymer membrane and on the catalyst surface, caused by high local temperatures, resulting from heat released by the fuel cell reaction and ohmic losses. The fact that current Nafion based polymers require water for proton conduction only complicates local conditions, i.e., any local drying of the polymer will cause further local temperature increase. In laboratory conditions, PEM fuel cells have exceeded 5,000 hours of continuous operation.

III. Fuel Cell System for Underwater Vehicles

A. Specific requirements

Requirements for application of fuel cells for propulsion of underwater vehicles may significantly differ from the requirements for applications current PEM fuel cells are being developed for. The main difference is obviously the choice of oxidant. Underwater use implies the use of stored oxidant, and therefore oxygen is practically the only choice. All other fuel cell terrestrial applications use air as oxidant.

The fuel cell uses hydrogen as fuel. Hydrogen/oxygen system produces no exhausts other than product water, which may be stored on-board to maintain neutral buoyancy. Use of other, hydrocarbon fuels such as gasoline, diesel, or methanol results in generation of CO_2. In addition, design and operation of small reformers in a variable load regime has proven not to be an easy task. The effects of impurities from fuel processor on fuel cell operation and longevity are not known yet, and durability of fuel processor catalysts is also questionable. Given the complexity and uncertainty of on-board fuel processing, plus the CO_2 issue, on-board hydrogen storage appears to be a better choice despite hydrogen bulkiness.

The efficiency requirement comes from the fact that the reactants must be stored on board. Higher fuel cell system efficiency results in smaller reactant storage vessels. At the same time, higher fuel cell efficiency means larger fuel cell. The efficiency and the size of the fuel cell is determined by the nominal cell voltage. The importance of fuel cell efficiency increases with duration of operation. Size and weight of the fuel cell system, including storage of reactants has a big effect on the design of the AUV itself. Careful selection and optimization of the nominal cell voltage and reactants storage option is required.

Hydrogen storage either as a liquid or compressed gas is considered a safety hazard. Although hydrogen has many properties that actually make it even safer than other fuels, the probability of a hydrogen leak is much higher than for any other fuel. This hazard may be significantly reduced by a proper and safe design of the entire system. Oxygen storage at high pressure is even more dangerous, and special design, material selection and cleaning measures must be applied.

B. System Configuration

A block diagram of a generic fuel cell system suitable for propulsion of the underwater vehicles is shown in Fig. 2. The heart of the system is the fuel cell stack which is served by the fuel supply, oxidant supply, cooling loop, and electrical subsystems. Fuel/hydrogen supply consists of the hydrogen storage, pressure regulator, humidifier, water separator and recirculation pump. Hydrogen is fed to the recirculation loop passively as it is consumed in the stack, i.e., no controls/regulation is necessary. Recirculation is needed to improve the flow inside the stack as well as to remove impurities and water that is condensing due to consumption of hydrogen or is back-diffusing through the polymer membrane. Humidification of hydrogen is required to maintain the membrane hydrated. Water and heat required for humidification may be supplied by the cooling loop.

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Oxygen is supplied in an identical manner. Oxygen circulation is required to facilitate removal of the product water from the stack. Liquid water is separated from reactants exhaust and collected in the tank. Water is used for cooling of the stack and for humidification of the both reactant gases. The heat from the fuel cell stack is rejected through a water cooled heat exchanger.

Fuel cell generates direct current with variable voltage. Voltage swings between the open circuit voltage (about 1 V/cell) and the nominal cell voltage which is an arbitrary value (typically between 0.6 V and 0.8 V) selected in the stack design process to meet the efficiency requirements. The stacks with up to 200 cells have been built and demonstrated. If the main load requires constant voltage a DC/DC power conditioner is required and if the load operates on AC then a DC/AC converter is required.

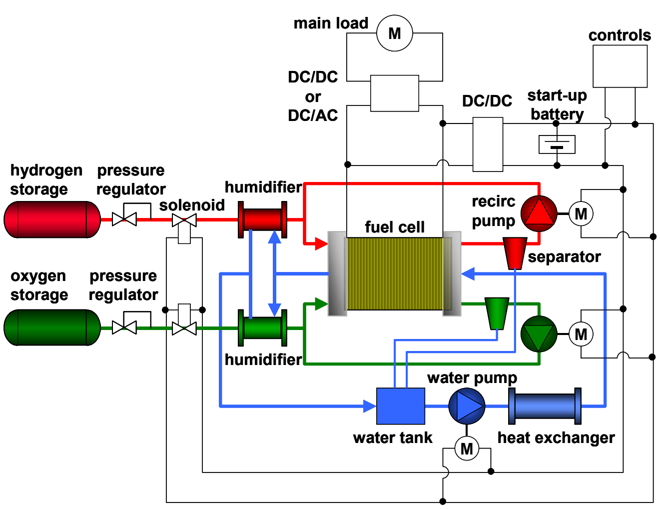

Fig. 2. Generic block diagram of a closed loop PEM fuel cell system

The ancillary components, pumps, solenoids and the controller, typically operate on 24 V DC, although recently 42 V is becoming more and more popular, especially for automotive applications. To power these components additional DC/DC inverter may be needed. Typically a start-up battery is included in the electrical subsystem. This battery energizes the solenoid valves on the fuel and oxidant supply lines. As soon as the fuel cell receives hydrogen and oxygen it is ready to operate, even at room temperature, and can take over from the battery and recharge it. The battery in Fig. 2 only serves for start-up. In such a system the fuel cell operates in a variable load regime and must be sized to the maximum required power. Another option is to use a smaller fuel cell with a battery bank. In this hybrid configuration the fuel cell may provide power only to a certain level, and the batteries are used for peaking. In another hybrid configuration all the power may come from the batteries and the fuel cell is used only for continuously recharging the batteries.

C. Fuel Storage Options

The amount of hydrogen/oxygen to be stored depends on the fuel cell system efficiency and duration of operation. Hydrogen may be stored as a liquid, compressed gas and in metal hydrides. Liquid hydrogen requires extremely low temperatures (20 K), gaseous hydrogen requires extremely high pressures (>200 bar), and metal hydrides require cooling and heating systems for charging and discharging respectively. Fig. 3 shows the mass and Fig. 4 shows the volume required to store 1 kg of hydrogen for different storage options, namely liquid hydrogen/liquid oxygen, compressed hydrogen/compressed oxygen, metal hydrides with liquid and compressed oxygen, and, just for comparison, methanol also with liquid and compressed oxygen. The weights and volumes in Figs. 3 and 4 include the reactants as well as the storage vessels.

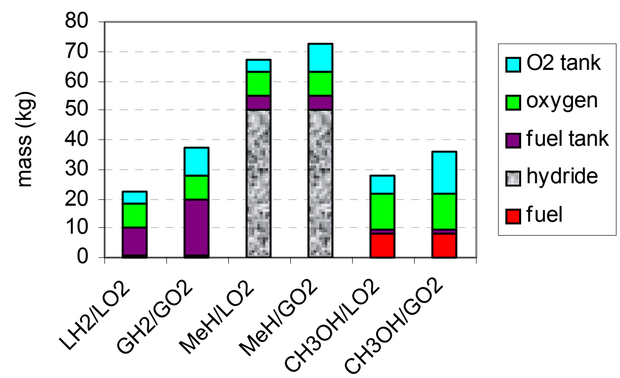

Fig.3. Mass of fuel and oxidant storage needed for 1 kg of hydrogen

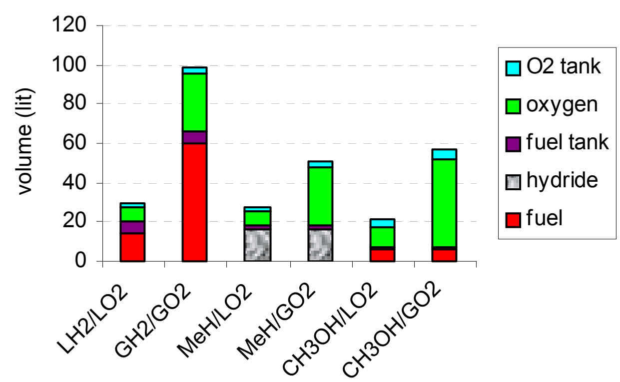

Fig. 4. Volume of fuel and oxidant storage needed for 1 kg of hydrogen

Liquid hydrogen/liquid oxygen option has the lowest weight and volume, compressed hydrogen/compressed oxygen is the bulkiest, and metal hydrides are comparable to liquid hydrogen storage, but are the heaviest option. Several metal hydrides may be used with PEM fuel cells. For example $FeTiH_2$ holds up to 1.9 wt% H_2, but it must be cooled while absorbing hydrogen under pressure (35 bar at 17°C). Desorption hydrogen pressure at 40°C is 7 bar, which is sufficient to operate the fuel cell. The Ti-V-Mn alloy has similar hydrogen capacity (1.8 wt%) and similar absorption/desorption characteristics, which also make it suitable for the use with PEM fuel cells. There are metal hydrides that can store more hydrogen (up to 4 wt.%) but have the desorption temperatures way above the PEM fuel cell operating range.

D. System Performance

Hydrogen consumption is a function of the fuel cell efficiency and it is given by (3). The efficiency is a function of the power output, and other than at extremely low power output (<10% of nominal) it is always higher than at nominal power. For that reason an average efficiency for any operational regime will be most likely higher than the efficiency at nominal power. As discussed above, the efficiency >60% should be achievable with the fuel cell system for AUVs, corresponding to hydrogen consumption of <0.05 kg/kWh.

Oxygen consumption is about 8 times hydrogen consumption, therefore it is <0.4 kg/kWh.

Water generation is a sum of hydrogen and oxygen consumption (<0.45 kg/kWh). However, the sum of hydrogen, oxygen and water at any given moment is constant, which means that the system operation has no effect on the AUV buoyancy. Product water is collected and used for humidification of reactant gases and for stack cooling.

The PEM fuel cell operates at temperatures between 60°C and 80°C. The operating temperature is maintained by water circulation through the fuel cell stack. Heat is generated at a rate of ~1 kW per kW of electrical power output. In a closed loop system, such as one depicted in Fig. 2, heat is taken away from the system by a heat exchanger and (to a lesser extent) by dissipation to the surrounding.

A closed loop system generates very little noise; only noise is coming from the water, hydrogen and oxygen pumps. This may be an important advantage over the systems with internal combustion engines in underwater applications.

E. Refueling options

Selection of storage option should, besides the system size and weight, and safety considerations, also take into account the availability of fuel. For example availability of liquid hydrogen is extremely limited and may be a determining factor in selection of storage options. Refueling of liquid hydrogen and oxygen requires special equipment and skills. One has to take into account the boil-off losses both during refueling and during storage (both on-board and off-shore).

Refueling of metal hydrides requires cooling. The temperature and the rates depend on the type of metal hydride used.

Storage of compressed gases is technically the simplest solution. Storage tanks with pressure up to 34 MPa (5,000 psig) have been demonstrated in automotive applications. Both hydrogen and oxygen may be generated by an electrolyzer. In this case several refueling options exist:

- A smaller electrolyzer is used to generate hydrogen and oxygen, which are then stored in the tanks at the refueling facility. The refueling process then includes controlled equalizing of the pressures in the tanks at the refueling facility and those on-board of AUV.
- Depending on the size of the on-board storage tanks, one option may be simply swapping the tanks.
- If storage of hydrogen and oxygen at the refueling facility is not desirable, the electrolyzer may be sized to refill the on-board tanks directly.
- The electrolyzer may be included in the on-board fuel cell system, resulting thus in a regenerative fuel cell system.
- A regenerative fuel cell system may have a stack that may serve both as a fuel cell and as an electrolyzer (this is called unitized regenerative fuel cell or reversible fuel cell).

A regenerative fuel cell (with either discrete or unitized stacks) is similar to the batteries. Its overall (roundtrip) efficiency is lower than that of the batteries, but the achievable power densities (in Wh/kg) exceed those of the best batteries by at least a factor of 2. Depending on the hydrogen and oxygen storage options and densities, energy density of 400 Wh/kg is achievable. Higher energy density is possible (up to 1,000 Wh/kg) if the structural elements of the vessel may be used for hydrogen/oxygen storage.

IV. CONCLUSIONS - ADVANTAGES OF FUEL CELLS FOR AUVS

PEM fuel cells may be an attractive option for propulsion of underwater vehicles including the AUVs. They offer several undeniable advantages, such as:

- High achievable efficiency (over 60%),
- Quiet operation,
- Low thermal signature,
- Neutral buoyancy,
- Depth independence of the process,
- Relatively quick recharging, and
- Good operational and control features.

The major disadvantages of PEM fuel cells are the size, weight and safety aspects of hydrogen and oxygen on-board storage.

Fuel cells are being developed and commercialized for other applications, such as propulsion of automobiles, and portable and stationary power generation. Applications for underwater applications may require some unique features in terms of fuel cell stack and system configuration, and choice of materials, which may preclude the use of the existing stacks and systems, and may require additional development and engineering.