Journal of Power Sources 71 (1998) 144–149

PEFCs for naval ships and submarines: many tasks, one solution

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Abstract

Polymer electrolyte fuel cells (PEFCs) for air-independent propulsion systems have been developed and tested under submarine conditions and are thus ready for submarine application. A demand analysis and the presentation of the requirements for naval surface ships and submarines will be followed by the description of the realisation concepts for PEFC propulsion plants. Based on the results of FC operation on board of a submarine and the system design for the new German submarine Class 212, synergy effects will be derived from that for surface ships. Finally, future aspects will be pointed out including PEFC propulsion for merchant ships. © 1998 Elsevier Science S.A.

Keywords: PEFC propulsion for naval ships; Air-independent propulsion (AIP) for submarines

1. Introduction

As early as 20 years ago PEFC systems were identified as the most efficient solution for air-independent propulsion of conventional submarines. In this context the special requirements of submarine propulsion systems played a decisive role. In those days PEFCs were used merely in the form of small power units in space applications. The consistent development of an air-independent propulsion system for submarines in Germany has brought out the PEFC from a niche application. Although the requirements on PEFC systems for naval surface ships differ considerably from those on submarines, their realisation can be based on the same components. In connection with this it is of great advantage that PEFCs for surface ships may be designed as air-breathing modules, in contrast to the use of pure oxygen on board of submarines.

2. Demand analysis and requirements for naval ships and submarines

The task of submarines is to perform defined missions undetected. This can be done by means of efficient propulsion systems only. The main requirements to be met by the propulsion system and the submarine are the following:

- extensive submerged endurance and
- low detectability (acoustics/sonar, heat/IR)

Over and above this, high submerged speed rates are required every now and then. Now the development of air-independent propulsion systems and their integration on board allows the submerged cruising range of a submarine to be increased considerably.

Due to the limited possibilities of conventional submarines to store sufficient energy, they are mostly operating at small output in the range of 3–5% of the rated capacity. The installed power capability of the propulsion system is defined by the maximum submerged speed required. The submerged endurance required defines the amount of reactants to be stored. Due to the necessity to meet the requirments of both low, permanent output and short-time peak output, it may be advantageous to install two different propulsion systems. These systems are purpose-adapted in terms of output and optimised with regard to efficiency, and are called hybrid systems.

For application on naval surface ships combined propulsion systems used hitherto, and consisting of diesel engines and gas turbines, have proved their worth. Steam turbines are merely used in exceptional cases. Of late, however, the ‘all-electric ship’ has been discussed by a couple of navies, and in connection with this the following criteria are of importance:

0378-7753/98/$19.00
PII S0378-7753(97)02717-1

Environment:

- pollution decreased by 95–99% (elimination of nitrogen oxides [NO_x], carbon monoxide [CO], hydrocarbons [HC])

Detectability (stealth):

- acoustic silence
- low thermal signature

Efficiency:

- increased range and mission capability
- decreased fuel costs

These criteria can be met advantageously by fuel cells.

For the time being systems offering power ranges from 1.5–2.5 MW are being taken into account for trials. In practice, ship propulsion systems provide a power range of about 8 MW (6 MW for propulsion, 2 MW for hotel load). The peak output required for reaching the maximum speed is provided by gas turbines. Compared to systems on board of submarines it is advantageous that air-breathing-type FC modules can be used. Reformer systems are foreseen for supplying the system with hydrogen, which generate hydrogen onboard from a logistic fuel (diesel fuel, kerosene). The use of high-temperature fuel cells, e.g. SOFCs, is planned for the future.

3. Realisation concepts

The submarines, more than 100, which have been built on the two German submarine yards HDW in Kiel and TNSW in Emden over the last 40 years are equipped with conventional, diesel-electric propulsion systems. The energy required for submerged operation, for propulsion and hotel load, is stored in a lead–acid battery. The continuous submerged cruising range of such submarines, i.e. the submerged distance without snorkelling, is limited merely by the capacity of the lead–acid battery. When discharged, the batteries are recharged during snorkelling by means of diesel generators. During this period the submarine is exposed to the higher risk of being detected. The development of air-independent propulsion systems and the integration of such systems on board permit the submerged endurance of a submarine to be increased considerably. In the field of combustion engines especially the closed-cycle diesel engine has been developed in Germany over the last 25 years, next to the Stirling engine and the closed-cycle gas turbine. However, it is the fuel cell that has excelled, most of all the PEFC, thanks to its very special advantages:

favourably low signature

- no noise
- minimum waste heat transfer to ambient seawater
- modular design of the entire propulsion system
- high efficiency, especially at partial load
- environmentally safe reaction products
- low maintenance requirements

The electrochemical conversion process allows the fuel cell to operate independently of the Carnot factor. This factor restricts the degree of thermal efficiency of combustion engines according to a ratio of minimum and maximum process temperatures. This allows the H_2/O_2 fuel cell to operate at a high level of overall efficiency amounting to approx. 60% at rated output. The particular characteristics of the system mean that maximum efficiency under partial load is achieved at about 20% load and 70% efficiency. If the FC plant is dimensioned with this operating load in mind, the fuel cell is by far superior to all other combustion engines with respect to fuel and oxygen consumption. Most recommendable for application on submarines are low-temperature fuel cells of PE technology. For this purpose the individual fuel cells are joined up to form FC stacks, which, in turn, form FC modules. Hence there is much flexibility when it comes to structuring FC propulsion systems.

Based on this knowledge, the German Ministry of Defence, by the end of the 1970s, commissioned the development of a special PEFC module for submarines from the manufacturer Siemens. Such modules, featuring a capacity range of 30–50 kW, are available nowadays as series-produced components for submarine application.

4. State of the art

The foundation for PEFC submarine propulsion systems was laid in the 1970s when the PEFC was selected and defined as propulsion system of the German submarine Class 208. The PEFC modules not having matured, the project was terminated in 1979. In the following years from 1980 to 1988 the functional suitability of a FC system geared to submarine propulsion was firstly tested on a shore test plant, and later in practical sea trials on board of a Class 205 submarine of the German Navy. At the beginning of the 1990s the development of hydrogen and oxygen storage on submarines reached the stage of series production, so that nowadays all components necessary for air-independent PEFC systems are available.

4.1. PEFC using hydrogen and oxygen (Siemens type)

As mentioned above, Siemens developed a 34-kW FC module over the last 10 years for use on board of submarines, at the request of the German MoD. This PEFC is operated using hydrogen and oxygen (Fig. 1). The modules are the core of the air-independent propulsion system of the new German Class 212 submarine. For onboard use the modules are protected by a pressure-tight container for rea-

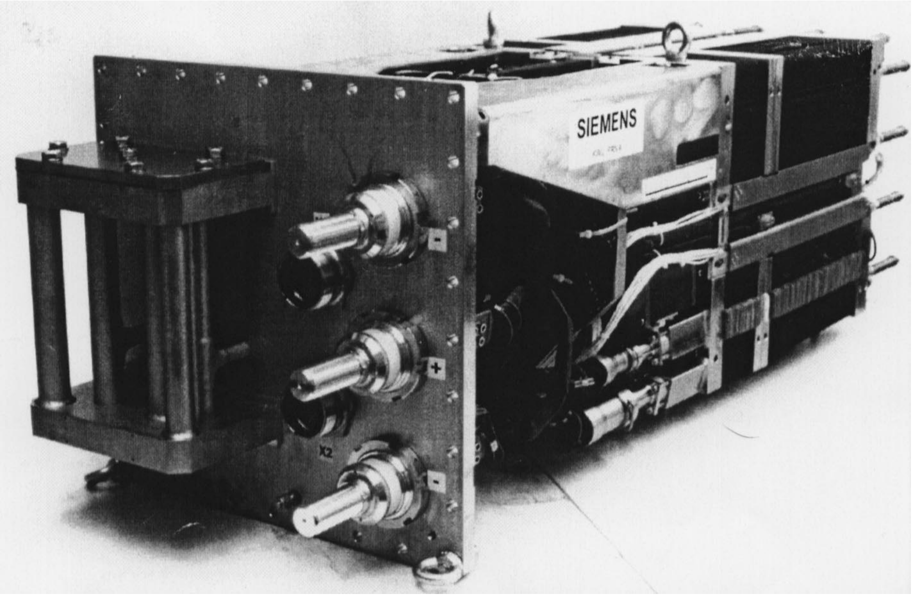

Fig. 1. 30–50 kW PEFC; Siemens.

sons of safety. The free container volume is filled with inert gas and monitored for leaks.

4.2. PEFC using hydrogen and air (Ballard type)

Based on the favourable environmental behaviour (low pollutant emission), Ballard in Canada are currently developing low-price PEFCs. These PEFCs are intended for hydrogen/air operation to be applied in stationary energy recovery plants and in transport (e.g. buses, automobiles). These fuel cells cannot run on pure oxygen, but when modifying them so as to operate with a nitrogen/oxygen closed-cycle gas compound, they can also be used for generating power on board of submarines. 1996/97 2 × 80-kW PEFCs were tested for submarine application on a shore test plant at the HDW yard in Kiel.

4.3. Storage of reactants

Onboard storage of hydrogen requires special storage vessels, no matter whether hydrogen is stored in gaseous or liquid form or bound in metal hydrides. It is most advantageous to store hydrogen on board of submarines bound in metal hydrides which are stored in storage cylinders outside the pressure hull. Low-temperature metal hydrides are particularly suitable for this purpose, featuring a reversible storage capacity of up to 2% of their weight. The quantity and dimensioning of the H_2 storage cylinders can be adapted to the design of the submarine and to the mission profile of the boat. In contrast to applications in automobile transport, the weight of the cylinders as such does not play an important role since a submarine is operative only if weight and buoyancy are balanced against each other. The metal hydride is melted in vacuum furnaces, conveyed and mounted in aluminium cassettes and provided with a steel shell. Hydrogen is added or drawn through a central filter pipe. During the first H_2 charging, which is the activating process, the cast metal block disintegrates into a fine powder. While hydrogen is absorbed, reaction energy is released, which must be added again during dehydration. For this purpose waste heat from the cooling water of the fuel cell system is used in onboard operation. This increases the efficiency of the system, while at the same time less excess heat must be transferred into the ambient seawater. Hence it is possible to store large amounts of hydrogen in small volumes at low to medium pressures and normal ambient temperature. The process of absorbing and releasing hydrogen is a reversible one. Stability of the cycle was proved in laboratory tests by running many thousands of cycles, using highly pure hydrogen. The metal hydride storage cylinders are completely maintenance-free so that they are easily accommodated in the outer hull of the submarine. It was HDW who built hydride storage cylinders of this size for the first time (Fig. 2) and who developed them for series production, the storage cylinders having undergone an ample test phase followed by sample testing. The results met all expectations.

However, the storage of hydrogen can be improved for submarines, but most of all for surface vessels, provided that hydrogen is generated on board from liquid hydrocarbons. Depending on the hydrocarbon used, the weight-related energy density is 4- to 8-times higher than that of pure hydrogen. On a surface vessel hydrogen is generated in a reforming process (steam reforming or partial oxidation). Partial oxidation, requiring an increased amount of oxygen, cannot take place on submarines where oxygen required for reforming must be stored on board instead of air. Methanol is recommended as basic medium for hydrogen generation

Fig. 2. Hydrogen storage in metal hydride cylinders.

because it can be reformed at temperatures below 300°C. On surface vessels a logistic fuel, e.g. diesel fuel or kerosene, is likely to be preferred for the reforming process, which, however, takes place at temperatures of about 900°C. Moreover, a more sophisticated system is necessary due to the content of sulfur in the fuel.

A steam reforming system (Fig. 3) for submarines comprises

- storing vessels for methanol
- storing vessels for oxygen
- a steam reformer assembly
- a gas purification stage
- a CO_2 handling system

CO_2 produced during reforming must be stored on board of the submarine or discharged into the ambient seawater in a suitable way, that is signature-free, and if possible, without requiring additional energy. A reformer system for generating hydrogen on board of submarines is currently under development and will be available for onboard application from the year 2000 on.

Oxygen is stored on board in liquid form either outside or inside the pressure hull. From the point of view of safety internal storage is just as acceptable as outside storage, but the former requires more sophisticated measures to ensure the same safety standard. The tanks are double-walled and vacuum-insulated (Fig. 4). Tank fittings, safety and monitoring equipment, as well as the product evaporator, are provided in a pressure-tight and water-tight fittings cabinet.- For reasons of shock the fittings and the evaporator are installed in a resiliently mounted rack. To give evidence of sufficient tank strength and insulation, the tank was exposed to extreme impact achieved in submarine shock tests. Oxygen for the crew in the submerged submarine is likewise provided from the oxygen stored onboard for supplying the FC system.

5. Experience

5.1. Shore test plant/submarine Class 205 ‘U1’

An important step on the way to developing fuel cells for submarines was the decision taken by the consortium consisting of HDW/IKL/FS in 1980 to design and erect a 100-kW FC system and to test its function under submarine conditions. The system comprised 16 × 6.2-kW modules of AFC technology, which was available from Siemens at that time. Four modules each were series-connected in order to correspond to the battery voltage of the ship’s network and the propulsion network. Four FC stacks were connected in parallel. Although AFC modules had to be used instead of PEFC, all relevant ambient conditions typical for submarine application could be taken into account in terms of function

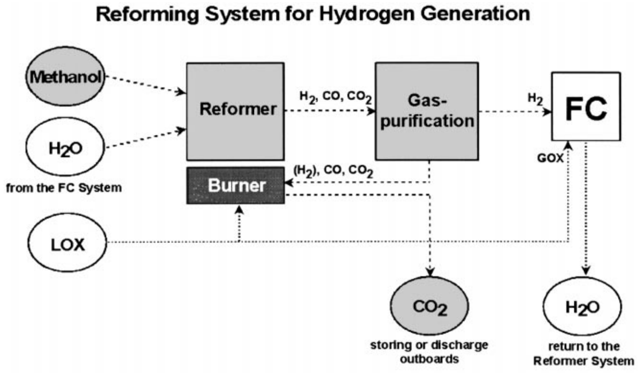

Fig. 3. Hydrogen generation from methanol (principle).

Fig. 4. Liquid oxygen storage tank.

and safety. Following a successfully finished test phase in a shore test plant which had taken place from 1983 to 1985, the FC system was integrated in U1, a Class 205 submarine of the German Navy, in 1986/87. In 1988/89 the system was tested in ample sea trials. For installing the FC system in the submarine, the pressure hull was cut in two and extended by a section about 3.70 m long. Cutting submarines in two so as to perform large-scale repair is now possible. In this way not only new submarines can be fitted with a PEFC system, but also boats in service within the scope of a mid-life refit.

5.2. PEFC system for class 212

The decision to fit the Class 212 submarines with fuel cell systems blazed a trail all over the world in favour of a new submarine generation. On the one hand these submarines mark a leap into next-generation technology, and on the other hand it is the first time that an air-independent system based on fuel cells will be integrated in a modern, conventional submarine (Fig. 5). The air-independent propulsion system comprises PEFC modules manufactured by Siemens for ultra-silent running. Given an FC output of about 300 kW the submarine will run on the FC system alone up to a speed of approx. 8 kts. For increased speed the high-capacity lead–acid battery will be connected. The propulsion motor will be a permanent-magnet-excited unit offering a low propeller speed. Hydrogen and oxygen, the supply gases for operating the FC system, will be accommodated in the second shell of the submarine in the external hull, hydrogen being stored in metal hydrides, oxygen in liquid form in insulated tanks. The Class 212 submarines are currently in the design phase and will be commissioned by the Navy from the year 2003 on. The construction phase

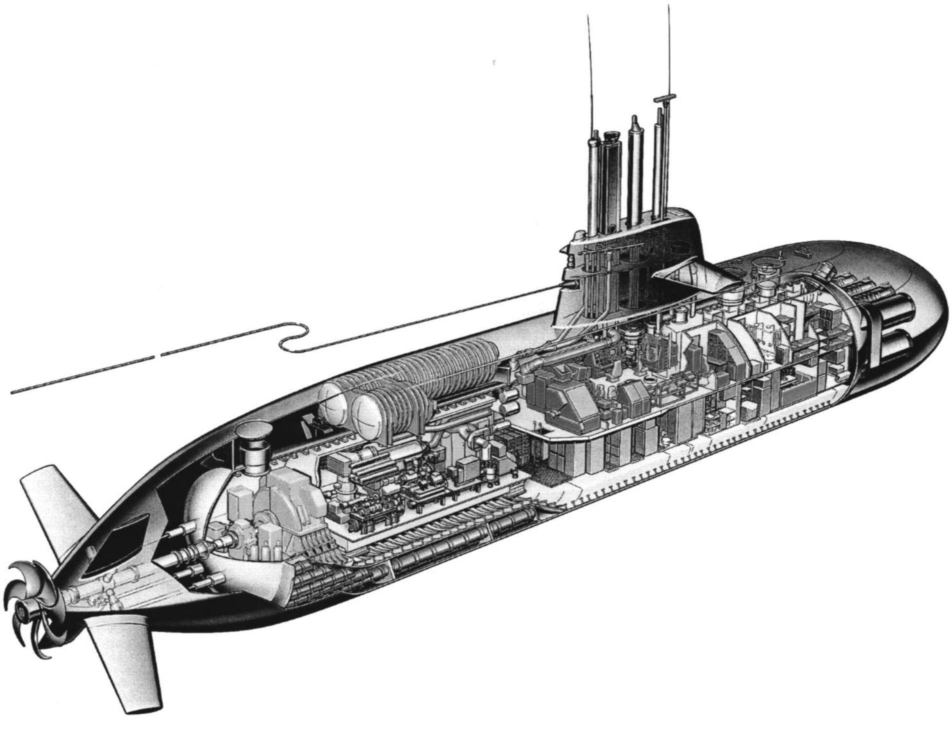

Fig. 5. Submarine Class 212.

of the four German boats has already commenced, while two identical boats for the Italian Navy will be built in Italy according to German plans.

6. Synergy

Siemens is currently developing a 120-kW PEFC, which is an advancement of the modules for the Class 212 submarines and has almost the same structural volume and weight. This module will begin to be series-produced around the year 2000. The power density of this module is 280 kW/m^3, its power/weight ratio 0.3 kW/kg. Based on this technology Siemens is developing a hydrogen/air FC module in a power range of 30–45 kW, which will be available for use on surface vessels also around the year 2000. Hydrogen required for operating this module can be stored on board, or, more conveniently, can be generated on board by means of a reformer from a logistic fuel, e.g. diesel fuel or kerosene.

6.1. Application of FC systems on merchant ships

It is possible to use FC systems for generating electrical energy and/or for propulsion purposes. Fuel cells are particularly suitable for the following applications:

- emergency power supply (e.g. passenger vessels, ferries)
- power generation, especially low emissions suitable for heavily polluted ports (e.g. container vessels)
- power generation/propulsive power for vessels placing strong emphasis on noise reduction (e.g. passenger vessels, research vessels)
- propulsive power for vessels boiling off hydrogen or methane (e.g. liquid hydrogen tankers, LNG tankers)

7. Future aspects

The decision taken by HDW/IKL/FS in 1980 to develop a fuel cell propulsion system for submarines not only paved the way for air-independent technology, but also for hydrogen technology in general. The 1970s marked the outset of fuel cell propulsion systems, while in the 1980s evidence was given that such a system can be realised in terms of functioning. In the 1990s a series-produced submarine, Class 212, is derived from the positive results of this technical development. As early as today, with the decision to generate hydrogen on board by means of a reformer system, we are facing a new generation of FC systems. The development stage required for this has been launched.