Energy 36 (2011) 3138–3147

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

Analysis of 3000 T class submarines equipped with polymer electrolyte fuel cells

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ARTICLE INFO

Article history:
Received 20 October 2010
Received in revised form
1 March 2011
Accepted 2 March 2011
Available online 2 April 2011

Keywords:
Polymer electrolyte fuel cells
Submarine
Air independent propulsion
Sodium borohydride
Metal hydride

ABSTRACT

The naval submarines have conventionally been equipped with diesel-electric propulsion. The diesel generators charge the batteries when the submarine is at the surface or at snorkelling depth. This is the biggest short-coming of this system as the submarine can be detected due to the infrared signatures from the exhaust of engines. Present study aims in analysing the feasibility of using fuel cells as a replacement of conventional diesel based system. Fuel cell system is analysed to meet the propulsion load and hotel load. In this purpose, metal hydride and sodium borohydride are considered for fuel and compressed oxygen and liquid oxygen are considered as oxidant. The most effective combination with respect to weight, volume has been analysed. The submerged endurance and distance for various hotel loads under submerged conditions have also been estimated. It is found that the metal hydride and liquid oxygen combination can be easily retrofitted by replacing the conventional system. However, MH/O_2, SBH/O_2 and SBH/LO_X require some extra room to be created. All the systems show substantial enhancement in the submerged endurance.

1. Introduction

Submarines are valuable assets to any Navy due to their inherent capability of sailing while submerged under water and launching attacks unnoticed. This makes its detection difficult and makes patrolling in hostile water at the time of conflict safer than ships. At present most of the submarines are diesel engine/battery propelled. However, the conventional diesel-electric submarines have their own limitations. The submerged time is limited by the capacity of batteries and they are prone to detection when surfaced for charging batteries or at few meters below the surface known as snorkelling depth. In addition to the strong infrared signature emitted by the exhausts of the diesel generators during snorkelling, the boats are susceptible to visual detection.

In order to enhance the submerged time of the existing submarines various options are available, aptly called 'Air Independent Propulsion' options as they facilitate the submarine to be submerged for prolonged duration by avoiding the need to surface for air access. These include Closed Cycle Diesel (CCD), Sterling engine, Module d'Energie Sous-Marin Autonome (MESMA), Closed Cycle Gas Turbine (CCGT) and low temperature fuel cells.

For low temperature operations, Polymer Electrolyte Fuel Cells (PEFCs) are the most favourable [1–18] option for submarines. Hydrogen for the reaction can mainly be stored onboard in the form of compressed gas [19,20], in liquid form at cryogenic temperatures [21] or in solid form in some hydrides [22,23]. Studies comparing all storage options [24–27] favour the storing of hydrogen and oxygen or air in gaseous state. However, for submarine applications compressed gases may not be an answer due to safety and reliability constraints. Sodium borohydride (SBH) can be considered as a hydrogen carrier [28–33] which might give higher weight percent of hydrogen storage than compressed hydrogen. Liquid oxygen (LO_X) is considered as the oxidant. Compressed air which is carried onboard in present system for other purposes has also been considered as a variant oxidant.

In the present work, a feasibility study has been carried out to equip a generic 3000 ton submarine by replacing the diesel based conventional system with PEFC and battery to work out the optimum combination, considering weight and volume, towards Air Independent Propulsion (AIP). Finally, the duration in submerged condition is being investigated for different combinations and compared with conventional system.

2. System description

Conventional diesel based electric submarines mainly comprise of diesel engines, battery banks, motors used for sprinting at high speed (14–16 knots; 1 knot ≈ 1.852 km h^{-1}) and sailing at low speed (4–5 knots). The diesel generators are mainly used to charge the batteries only when the submarine has the access to the

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doi:10.1016/j.energy.2011.03.003

Nomenclature

D	submerged displacement [kg]
E_{vol}	volumetric energy density of hydrogen [kW h m^{-3}]
E_{BAT}	energy supplied by battery bank [kW h]
E_{hotel}	daily energy demand by hotel load [kW h d^{-1}]
E_T	daily energy demand [kW h d^{-1}]
E_{hor}	energy required for leaving and entering harbour [kW h]
$E_{store}{}^W$	total stored energy in the submarine based on available weight [kW h]
$E_{store}{}^V$	total stored energy in the submarine based on available volume [kW h]
M_{H_2}	molecular weight of hydrogen [g mol^{-1}]
N_{H_2}	number of moles of hydrogen
N_{O_2}	number of moles of oxygen
P_{AV}	average power required from fuel cell [kW]
P_{FC}	fuel cell stack size [kW]
P_{eco}	propulsion power at economic speed [kW]
P_{prop}	propulsion load [kW]
P_{sprint}	propulsion power at high speed [kW]
P_{hotel}	hotel load [kW]
P_{tank}	oxygen tank pressure [MPa]
$Q_{batbank}$	battery bank capacity [kW h]
Q_{PERC}	battery storage capacity [%]
S	total distance travel by submarine [km]
$T_{end}{}^W$	endurance based on weight [d]
$T_{end}{}^V$	endurance based on volume [d]
T_{DIS}	ratio of discharge rate
T_{NOM}	nominal discharge [h]
T_{ACT}	actual discharge [h]
T	time of battery operation per day [h d^{-1}]
T_{eco}	total propulsion time at low speed [h]
T_{sprint}	total propulsion time at high speed [h]
V_{DGBAT}	available volume in submarine [m^3]
V_{SBH}	volume of sodium borohydride [m^3 d^{-1}]
V_{H_2O}	volumes of water [m^3 d^{-1}]
V_{BOP}	volume of balance of plant [m^3]
V_{H_2}	volume of hydrogen at STP [m^3 d^{-1}]
V_{O_2SYS}	volume of the compressed oxygen storage system [m^3 d^{-1}]
V_{LO_xSYS}	volume of the liquid oxygen storage system [m^3 d^{-1}]
V_{H_2SYS}	total volume of hydrogen storage system [m^3 d^{-1}]
V_{SBHSYS}	total volume of sodium borohydride storage system [m^3 d^{-1}]
$V_{fuelsys}$	total volume of fuel system [m^3 d^{-1}]
V_{oxisys}	total volume of oxidant system [m^3 d^{-1}]
$W_{fuelsys}$	total weight of fuel system [kg d^{-1}]
W_{oxisys}	total weight of oxidant system [kg d^{-1}]
W_{SBH}	weight of sodium borohydride [kg d^{-1}]
W_{H_2O}	weights water [kg d^{-1}]
W_{BOP}	weight of balance of plant [kg]
WT_{perc}	gravimetric storage in wt%
W_{DGBAT}	available weight in submarine [kg]
W_{LO_xSYS}	weight of liquid oxygen system [kg d^{-1}]
W_{O_2}	weight of oxygen [kg d^{-1}]
W_{H_2}	weight of hydrogen [kg d^{-1}]
W_{H_2SYS}	weight of hydrogen storage [kg d^{-1}]
W_{SBHSYS}	total weight of sodium borohydride storage system [kg d^{-1}]
p_{gra_FC}	gravimetric power density of fuel cell stacks [kW kg^{-1}]
p_{vol_FC}	volumetric power density of fuel cell stacks [kW m^{-3}]
r_{grav}	gravimetric fraction LO_X
r_{vol}	volumetric fraction LO_X
u	speed of the submarine [km h^{-1}]
v_{eco}	propulsion power at low speed [km h^{-1}]
v_{sprint}	propulsion power at high speed [km h^{-1}]

Greek symbols

ΔH	higher heating value [kW h mol^{-1}]
η_{DOD}	depth of discharge of the battery bank
$\eta_{OVERALL}$	overall efficiency
η_B	battery efficiency
$\eta_{DC/DC}$	efficiency of DC/DC converter
η_{FC}	efficiency of fuel cell
ρ_{LO_X}	density of liquid oxygen [kg m^{-3}]

atmosphere, enabling combustion. The batteries fulfill the total energy requirements of the submarine during submerged condition. The schematic diagram of a conventional submarine is shown in Fig. 1.

The total load requirement of the submarine is categorised mainly as hotel load and propulsion load. The propulsion load of the submarine is a function of the speed (u) and the submerged displacement (D) which is given by [5],

$$P_{prop} = 0.0026 \cdot \left(\frac{D}{1000}\right)^{2/3} \cdot \left(\frac{u}{1.852}\right)^3 \quad (1)$$

The peak power requirement is mainly controlled by the maximum attainable speed of the submarine.

In addition to the propulsion load, the submarine has a large set of equipments, which include pumps and blowers, communication sets, life support systems, domestic appliances, control systems and armament. The hotel loads generally remain constant for specific requirements and it may vary between 100 kW and 475 kW based on the requirements.

However, the operating duration and total energy consumptions by different equipments vary widely. To estimate the load profile for the submarine, it is assumed that the submarine sails at a speed of 5 knots using low speed motor for 22 h and sprints using high-speed motor for 2 h at 16 knots each day. During two hours of sprinting, it requires almost 5805 kW h. However, two hours of sprinting time is subject to variation depending upon practical speed requirements and situation demands. The assumed typical daily load profile is shown in Fig. 2.

The load profile shows three distinct levels of operation. High-speed motor and low speed motor cover the propulsion load while pumps cover all pumps used onboard. The miscellaneous head includes the energy consumed during entering and leaving harbour, air compressors and domestic load. The other heads include load of air conditioning and refrigeration system besides alternator loads.

The total weight and volume of the system used for power generation and energy storage is important as it is planned in the

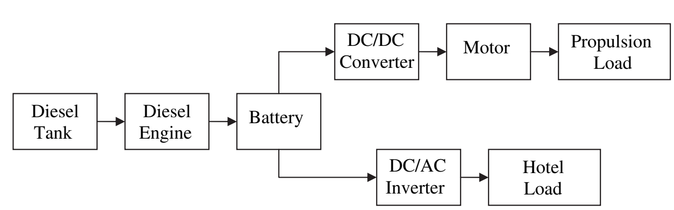

Fig. 1. Schematic diagram for the conventional system.