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Early-Stage Analysis of Air Independent Propulsion Based on Fuel Cells for Small Submarines

H. Nguyen Ha, Q. Nguyen Quoc*, and P. Cu Xuan

Faculty of Vehicle and Energy Engineering, Le Quy Don Technical University, Hanoi, Vietnam

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Abstract:

This paper presents an analysis of the results of a hybrid air independent propulsion based on fuel cells for small submarines. The weight and volume of the investigated propulsion, and the major tactical and technical characteristics of the 540-tonne submarine equipped with this propulsion have been determined. Five onboard systems for the hydrogen storage or generation, and the oxygen storage are considered. Combining a micro-balloon hydrogen system with the cryogenic oxygen storage is the best solution for the propulsion. The submerged endurance and range improved 32.1-64.8 times, as compared to just battery. The indiscretion ratio equals zero at cruising speeds of less than 7.1 knots, while at higher speeds, this value has dramatically decreased, and submarine secrecy has increased significantly.

Keywords:

air independent propulsion, fuel cell, indiscretion ratio, submarine, endurance

1 Introduction

Submarines are advantageous to navies because they can maneuver undersea, and conduct strikes undetected. In addition, the world is presently concentrating on the development of small submarines, which typically have a submerged displacement of less than 600 Mg [1], are equipped with diesel generators and lithium-ion batteries, and in some cases feature an air independent propulsion system (AIP).

In conventional diesel-electric power plants, electricity generated by diesel generators (DG) is stored in a battery bank (BB) and used to power electric propulsion motors (PM). Traditional diesel-electric submarines are limited in their submerged sailing time due to the little amount of energy in their BB. For recharging BB, submarines must float to the surface or use a retractable equipment for diesel operation at

* *Corresponding author: Faculty of Vehicle and Energy Engineering, Le Quy Don Technical University, Hoang Quoc Viet 236, Hanoi, Vietnam. Phone +84964 14 02 84, Email: ngquanturbine@lqdtu.edu.vn. ORCID 0000-0002-1704-0741.*

snorkeling depth, which increases the likelihood of detection by radar, infrared, optoelectronic, and acoustic sensors. An air independent propulsion is utilized to boost submerged endurance, submerged range, and stealth, which can function as an auxiliary power source.

Small submarines utilize multiple types of AIP, including Closed Cycle Diesel, Stirling Engine, and polymer electrolyte membrane fuel cell (PEMFC) [2, 3]. This paper examines a hybrid AIP formed from the combination of BB and PEMFC since PEMFC is effective in the long-term load mode, whereas BB is most successful in short discharge-charge cycles.

A PEMFC is a system that directly converts the chemical energy of the fuel into electrical energy. The reaction's fuel (hydrogen) can be stored aboard as a compressed gas [4], a liquid at cryogenic temperatures [5-7] (liquid hydrogen - LH_2), or as a solid in certain metal hydrides and intermetallic compounds (MH_2) [2, 5, 7, 8]. In addition, hydrogen can be obtained through the hydrolysis of sodium borohydride (SBH) [2, 3] and stored in a micro-balloon system (MBS) [8, 9]. Liquid oxygen (LOX) is a universally accepted oxidant for all AIP types without exception [8].

This work aims to analyze a newly proposed hybrid AIP based on PEMFC for small submarines in terms of its weight and volume characteristics with various existing and promising storage/generation of reagents, a feature of navigation modes. The study objective is to determine the necessary submarine power, weights and volumes of permanent equipment, energy reserves, designed and submerged endurance, submerged range, and indiscretion ratio.

2 Description of the Hybrid AIP and Input Data

The hybrid AIP includes the following components: diesel generators, electric propulsion motors, battery bank, fuel cells, electrical converters and inverters, shafting (Sh), onboard consumers (hotel load), and fuel and oxygen storage systems (Fig. 1).

The required power of the hybrid AIP could be expressed as:

$$N = N_p + N_h \quad (1)$$

where N_p [kW] is the propulsion power, and N_h [kW] is the power for onboard consumers. The power for losses in cables and cable runs is read into the plant efficiency.

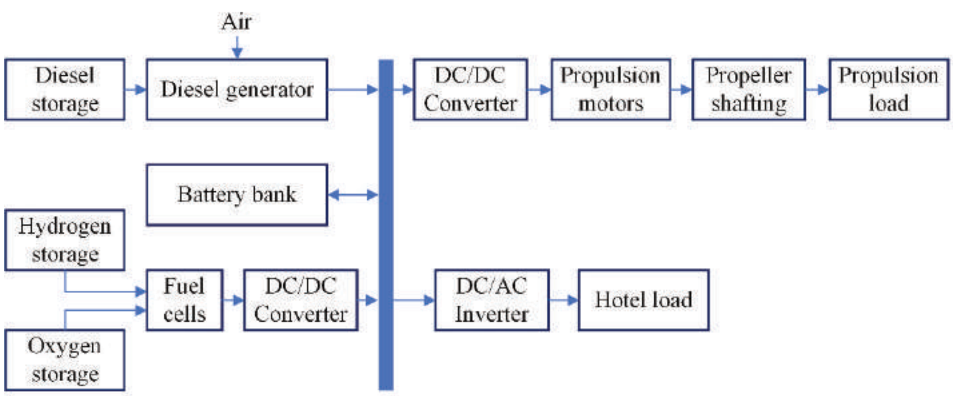

Fig. 1 Schematic diagram for the hybrid AIP based on fuel cells

An estimate of the required power of the hybrid AIP in the underwater mode, N [kW] is determined by the following expression [3]:

$$N = \left[\left(D/22 \right) + 25 \right] + 0.075 N_{FC} + 0.0026 D^{2/3} v^3 \tag{2}$$

where D is the submerged displacement [Mg], v is the submerged speed [knot – kn], and N_{FC} is the maximum power of the fuel cell [kW].

In Eq. (2), the first term represents the normal hotel load, the second term is the additional power supplied by the fuel cells to the hotel load, and the third term indicates the primary propulsion power.

In the early design stage of the hybrid AIP based on fuel cells, the small submarine with the normal displacement $D_0 = 485$ Mg, and the submerged displacement $D = 540$ Mg is considered. This small submarine has specifications similar to Turkish small submarine STM-500 [1]. The maximum power of the fuel cell $N_{FC} = 120$ kW is taken, equal to the power of fuel cells type BZM-120 [8, 10]. The required power of the submarine is shown in Fig. 2.

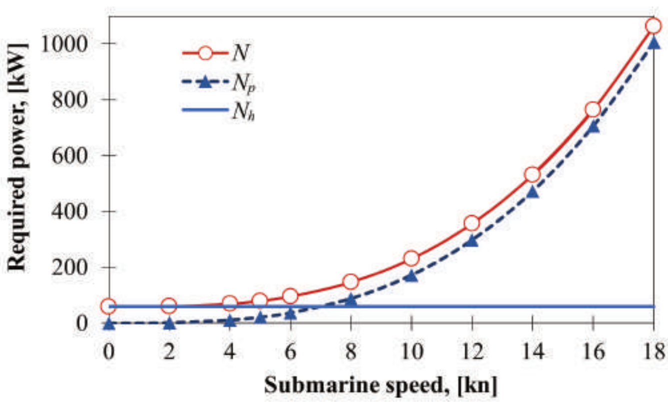

Fig. 2 Power required in relationship to the submerged speed

Fig. 3 proposes an analytical sequence between the weight and volume of a hybrid AIP and the primary tactical and technical characteristics of the submarine during the early-stage design. The number in parentheses is the formula for the related computation.

The transition to the area of operations of the submarine will be carried out by alternating the mode of movement under snorkeling, patrolling, and sprinting. A study of the velocity spectrum for small submarines shows that the share of high-speed underwater accounts for no more than 5 % of the total travel time. Therefore, this study assumes the daily energy requirements are divided into three parts.

The first part consists of 1 hour of high-speed operation with a maximum speed of 18 knots, while the second part consists of 20 hours of patrolling at low speeds of 5 knots. While the fuel cells produce the necessary energy in the second part, a part of this energy will be used to maintain the battery in a condition of total saturation, accounting for losses during self-discharge. The last part consists of 3 hours of snorkeling at a speed of 5 knots. In this scenario, the diesel generator produces the necessary energy while simultaneously charging the battery to its full capacity. Considered constant is the efficiency of fuel cells, battery banks, and electrical converters/inverters.

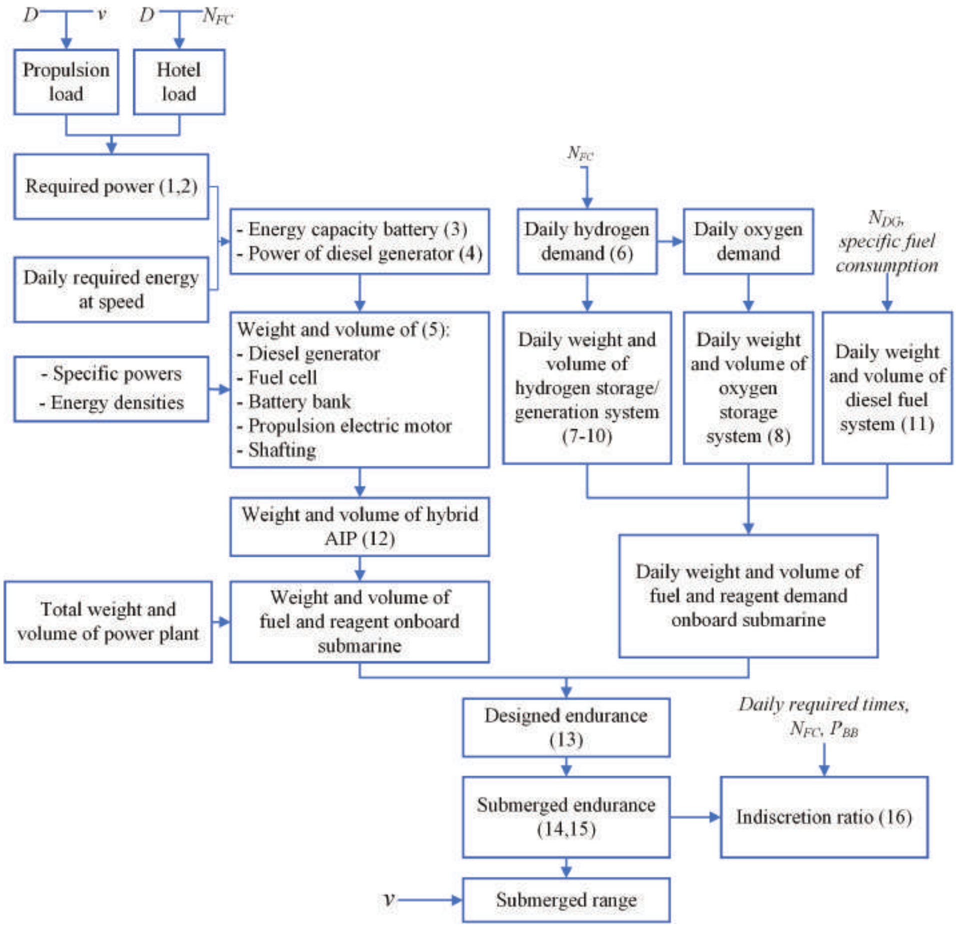

Fig. 3 Analytical sequence diagram for a hybrid AIP

Based on the above assumptions and data in Fig. 2, the capacity of battery bank P_{BB} [kWh] is determined by the following expression:

$$P_{BB} = 1 \cdot \left(\frac{N_p}{\eta_c \cdot \eta_m \cdot \eta_{sh}} + \frac{N_h}{\eta_i} \right) \tag{3}$$

where N_p = 1 010 kW is the propulsion power at v = 18 kn, N_h = 59 kW is the hotel load, η_c = 0.90, η_m = 0.95, η_{sh} = 0.99 and η_i = 0.90 are the efficiency of converters, motors, shafting, and inverter, respectively.

The power of the diesel generator N_{DG} [kW] is calculated by the formula:

$$N_{DG} = \frac{N \cdot 3 + P_{BB}}{3} \tag{4}$$

where N = 80 kW is the required power at v = 5 kn.

The capacity of battery bank P_{BB} = 1 260 kWh, and the power of the diesel generator N_{DG} = 500 kW are determined.

The specific power and efficiency of DG (Tab. 1) have been chosen based on the analysis results of marine diesel-generators with the power of approximately 500 kW (such as marine diesel-generators C18 and C9.3 of Caterpillar Co. [11], 6M26.2 and 6M26.3 of Baudouin Co. [12], KTA19-D of Cummins Inc. [13]). The energy density of the storage system is described in Tab. 2.

Tab. 1 Specific powers and efficiency for the equipment

Equipment	Gravimetric specific power, [kW/kg]	Volumetric specific power, [kW/l]	Efficiency, [%]	References
Diesel generator	0.045	0.033	40	[5]
Fuel cells (BZM-120)	0.133	0.257	55	[8, 10]
Propulsion motor	0.07	0.10	95	[13]
Shafting	0.24	1.87	99	[13]

Tab. 2 Energy densities of storage systems

Storage system	Conditions	Gravimetric energy density, [kWh/kg]	Volumetric energy density, [kWh/l]	Depth of discharge, [%]	References
Li-ion battery	—	0.15	0.20	80	[7, 9]
Metal hydride	$NaAlH_4$	0.40	0.38	100	[15]
Liquid hydrogen	1 bar 22 K	1.85	1.34	100	[15]
Liquid oxygen	1 bar 90 K	2.47	2.77	100	[15]

3 Analysis of Weight and Volume of Hybrid AIP

3.1 Weight and Volume of Equipment

The weight M_x [kg] and volume V_x [m^3] of DG, fuel cells, BB, PM and shafting depend on the specific powers or energy densities and the efficiency [6, 7]. They are calculated by the following expressions, respectively:

$$M_x = N_x / (g_x \cdot \eta_x)$$
$$V_x = N_x / (\gamma_x \cdot \eta_x) \tag{5}$$

where N_x is the power or energy capacity, g_x, γ_x and η_x are the gravimetric/volumetric specific power or energy density, and efficiency of the respective equipment. These data are given in Tabs 1 and 2.

3.2 Weight and Volume of Fuel and Oxidant Systems

Daily hydrogen demand: Regardless of the type of storage system, the total hydrogen amount in moles required for the total energy demand will be:

$$N_{H_2} = 3600\frac{N_{FC}\cdot 20}{\Delta H}\cdot\frac{1}{\eta_{overall}} \qquad (6)$$

where ΔH = 286 kJ/mol is the higher heating value (HHV) of hydrogen; $\eta_{overall}$ is the overall efficiency of the power plant, $\eta_{overall} = \eta_{FC}\cdot\eta_e$, here $\eta_e = 0.9$ is the efficiency of electrical converters/inverters, losses in cables and routes. The HHV is considered because PEMFC in this work always operates at temperatures below 100 ºC.

The daily weight of hydrogen:

$$M_{H_2} = N_{H_2}\cdot\mu_{H_2}\cdot 10^{-3}$$

where μ_{H_2} is the molecular mass of hydrogen, g/mol.

Micro-balloon storage system (*MBS*)*:* Hydrogen can be stored under high pressure in micro-balloons as spherical vessels made of glass or polymers with a 20-600-micron radius. Micro-balloons are filled with hydrogen at 473-673 K by diffusion of gas molecules through the walls [8].

The relative weight content of hydrogen in the micro balloon is 0.3 [8]. The mass and the volume are calculated by the Clapeyron equation with a correction factor z at high pressure:

$$\begin{aligned} M_{MBS} &= M_{H_2}/0.3 \\ V_{MBS} &= zM_{H_2}R_{H_2}T/(p\varphi) \end{aligned} \qquad (7)$$

where $z = 2.21$; $p = 200$ MPa; R_{H_2} = 4 124 J/(kg·K); $T = 323$ K; $\varphi = 0.74$ (fill factor).

Hydrogen storage system in hydrides (*MH_2*)*:* Metal hydrides, for example, MgH_2, LiH, NaH, CaH…, or intermetallic compounds, such as $NaAlH_4$, $LaNi_5H_6$, $TiFeH_2$, Mg_2NiH_2, $CeCO_3H_{4.5}$, can act as hydrogen accumulators.

Cryogenic storage of hydrogen: Hydrogen can be stored by freezing at temperatures below 20.15 K; this type of hydrogen is called liquid hydrogen (LH_2).

Cryogenic oxygen storage (*LOX*)*:* This work uses a cryogenic tank of liquid oxygen. The boiling point of oxygen is −183 ºC (90 K).

Chemical reaction in fuel cells [10]:

$$2H_{2,\ anode} + O_{2,\ cathode} \rightarrow 2H_2O_{,\ cathode.}$$

According to this reaction, the daily oxygen weight is determined $M_{O_2} = 8\cdot M_{H_2}$ and the daily oxygen volume $V_{O_2} = 8M_{H_2}/\rho_{O_2}$, here ρ_{O_2} = 1.141 kg/l is the LOX density.

The daily weight and volume of MH_2, LH_2 or LOX are calculated from the gravimetric and volumetric energy densities according to the formulas:

$$\begin{aligned} M_{MH_2,LH_2,LOX} &= N_{FC}\cdot 20/\left(g_{MH_2,LH_2,LOX}\cdot\eta_{overall}\right) \\ V_{MH_2,LH_2,LOX} &= N_{FC}\cdot 20/\left(\gamma_{MH_2,LH_2,LOX}\cdot\eta_{overall}\right) \end{aligned} \qquad (8)$$

where $g_{MH_2,LH_2,LOX}$ and $\gamma_{MH_2,LH_2,LOX}$ are the gravimetric and volumetric energy densities (Tab. 2).

Hydrogen production by hydrolysis of $NaBH_4$*:* Sodium borohydride (SBH) can be used as a source of hydrogen onboard submarine [16].

The hydrolysis reaction proceeds according to the equation:

$$NaBH_4 + 2H_2O \rightarrow NaBO_2 + 4H_2\uparrow + 117.39\ \text{kJ/mol},$$

therefore, to generate hydrogen from $NaBH_4$, water must be supplied.

The total weight of the SBH system:

$$M_{SBH} = M_{NaBH_4} + M_{H_2O} + M_{au} \tag{9}$$

where M_{au} is the weight of auxiliary equipment of the system, assuming $M_{au} = 10\ \% M_{SBH}$ [2]; M_{NaBH_4} and M_{H_2O} are the weights of $NaBH_4$ and H_2O, respectively, and they are determined by formulas:

$$M_{NaBH_4} = \left(N_{H_2}/4\right)\mu_{NaBH_4} \cdot 10^{-3}$$
$$M_{H_2O} = \left(2N_{H_2}/4\right)\mu_{H_2O} \cdot 10^{-3}$$

where μ_{NaBH_4} and μ_{H_2O} are the molecular mass of $NaBH_4$ and water, [g/mol].

The total volume of the SBH system is determined similarly by Eq. (9).

Hydrogen production by hydrolysis of aluminium powder: The experiments [8, 16] showed that under specified conditions, the process could be implemented by the reaction:

$$2Al + 3H_2O \rightarrow Al_2O_3 + 3H_2 \uparrow$$

According to this reaction, the weight of Al and H_2O will be:

$$M_{Al} = (2N_{H_2}/3)\mu_{Al} \cdot 10^{-3}$$

where $\mu_{Al} = 27$ g/mol; $M_{H_2O} = (3N_{H_2}/3)\mu_{H_2O} \cdot 10^{-3}$.

The total weight of the Al-H_2O system is determined in the same way as SBH system, including hydrolysis reactor, storage tank, filters, water heaters, steam condensers, pumps, pipes, etc. The total system volume is determined by [8]:

$$V_{Al\text{-}H_2O} = 3\left(V_{Al} + V_{H_2O}\right) \tag{10}$$

where $V_{Al} = M_{Al}/\rho_{Al}$, $\rho_{Al} = 2\ 700$ kg/m^3 and $V_{H_2O} = M_{H_2O}/\rho_{H_2O}$, $\rho_{H_2O} = 1\ 000$ kg/m^3 (in the temperature of 4 ºC).

Diesel fuel storage: The daily weight and volume of diesel fuel consumption:

$$M_{DF} = 3 \cdot g_{DF} \cdot N_{DG}$$
$$V_{DF} = M_{DG}/\rho_{DF} \tag{11}$$

where $g_{DF} = 0.215$ kg/kWh is the specific fuel consumption in the snorkeling mode, and $\rho_{DF} = 860$ kg/m^3 is diesel density [10].

4 Primary Tactical and Technical Characteristics

4.1 Designed Endurance

The designed endurance is the maximum days of submerged mode with reagent supplying on board and the proposed daily energy requirement related to the total weight or volume of hydrogen and oxygen.

The total weight and volume of the hybrid AIP are written as:

$$M_{AIP} = M_{DG} + M_{FC} + M_{BB} + M_{PM} + M_{Sh}$$
$$V_{AIP} = V_{DG} + V_{FC} + V_{BB} + V_{PM} + V_{Sh} \tag{12}$$

The designed endurance with different combinations of reagent systems is carried out according to the following expressions for MBS + LOX, MH_2 + LOX, LH_2 + LOX, SBH + LOX and Al-H_2O + LOX, respectively:

$$t_i = \left(0.3D_0 - M_{\mathrm{AIP}}\right) / \left(M_{\mathrm{system\_H_2}} + M_{\mathrm{LOX}} + M_{\mathrm{DF}}\right) \tag{13}$$

where $0.3D_0$ is the total weight of the power plant [6, 10], $M_{\mathrm{system\_H2}}$ is the weight of the hydrogen storage/generation systems.

Similarly, the designed endurance in volume with different combinations of reagent systems is carried out according to higher expressions with the replacement of $0.3D_0$ by $0.5V_0$, where $V_0 = D_0/\rho_0$, here $\rho_0 = 1\,025$ kg/m^3 is the sea water density.

4.2 Submerged Endurance and Range

The submerged endurance with various reagent combinations:

$$T_{\mathrm{i}} = 20 \cdot N_{\mathrm{FC}} \cdot t_{\mathrm{i}} / N \tag{14}$$

where i is the variant of combinations of reagent systems, N is the required power, determined by Eq. (2) depending on the submerged speed with $N < 120$ kW.

At $N \geq 120$ kW, the PEMFC provides power to the hotel load, then

$$T_{\mathrm{i}} = \left(20 \cdot N_{\mathrm{h}} \cdot t_{\mathrm{i}} + P_{\mathrm{BB}}\right) / N \tag{15}$$

The submerged range is determined by the submerged endurance and speed.

4.3 Indiscretion Ratio

The ratio of navigation time under the snorkeling, necessary for charging the battery, to the total time of navigation is determined by the stealth loss coefficient or indiscretion ratio k_i [3]:

$$k_{\mathrm{i}} = t_{\mathrm{s}} / \left(t_{\mathrm{s}} + t_{\mathrm{d}}\right) \tag{16}$$

where t_{s} is the time spent snorkeling to recharge the battery to its original state, and t_{d} is the battery discharging time.

When using the diesel generators and the battery bank $t_{\mathrm{s}} = 3$ hours and $t_{\mathrm{d}} = P_{\mathrm{BB}}/N$; when $N < 120$ kW, only the PEMFC is used, then $t_{\mathrm{s}} = 0$, and so $k_{\mathrm{i}} = 0$. When $N \geq 120$ kW, the diesel generators, battery bank and PEMFC are used together, while the battery bank provides power for propulsion, and PEMFC provides power for supplying hotel load. Then:

$$t_{\mathrm{s}} = 3T_{\mathrm{i}} \quad \text{and} \quad t_{\mathrm{d}} = \left(P_{\mathrm{BB}} / N_{\mathrm{P}}\right) T_{\mathrm{i}}$$

5 Results and Discussion

The results of calculations of the weight and volume of the hybrid AIP are presented in Tab. 3. The daily requirement of reagents and their systems was presented in Tab. 4.

The designed endurance is presented in Fig. 4 with five different hydrogen storage/generation systems. In all combinations, the oxidizing agent is liquid oxygen. Based on the daily requirement of the reagent system and the designed endurance, a comparison is made between the weights of reagents and their various storage/generation methods. The graph demonstrates that endurances are determined by weight rather than volume. In further study, therefore, the designed endurance is calculated just by weight. Maximum endurance when using MBS is 33 days, and minimal endurance when using MH_2 is 6 days.

Tab. 3 Weight and volume of the primary equipment

Equipment	Weight, [Mg]	Volume, [m^3]
Diesel generator	27.76	37.85
Fuel cells	1.64	0.85
Li-ion battery	10.49	7.87
Propulsion motor	15.35	10.74
Shafting	0.26	0.04
AIP	55.49	57.34

Tab. 4 Daily weight and volume of fuel and oxidant systems

Systems	Weight, [Mg/day]	Volume, [m^3/day]
MBS	0.41	2.43
MH_2	12.12	12.76
LH_2	2.62	3.62
SBH	1.25	1.21
Al	2.44	4.52
LOX	1.96	1.75
DF	0.32	0.38

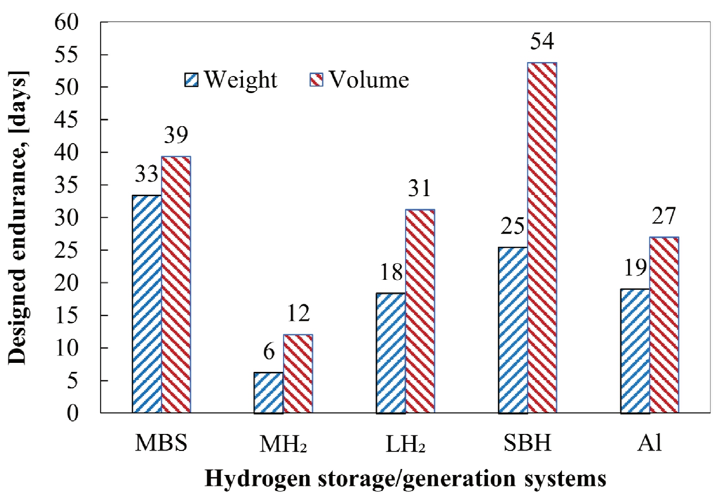

Fig. 4 Designed endurance with different combinations of the reagent systems

A comparison of the weight of reagents and their various storage/generation methods is performed based on the daily demand of the reagent system and the designed endurance (Fig. 5). In addition, the abscissa displays 5 different reagent storage/generation methods. The numbers in the graph columns represent, respectively, the weights of the reactants and their corresponding systems. The total weight of all systems is about same, while the hydrogen and oxygen weights in MBS are the greatest.

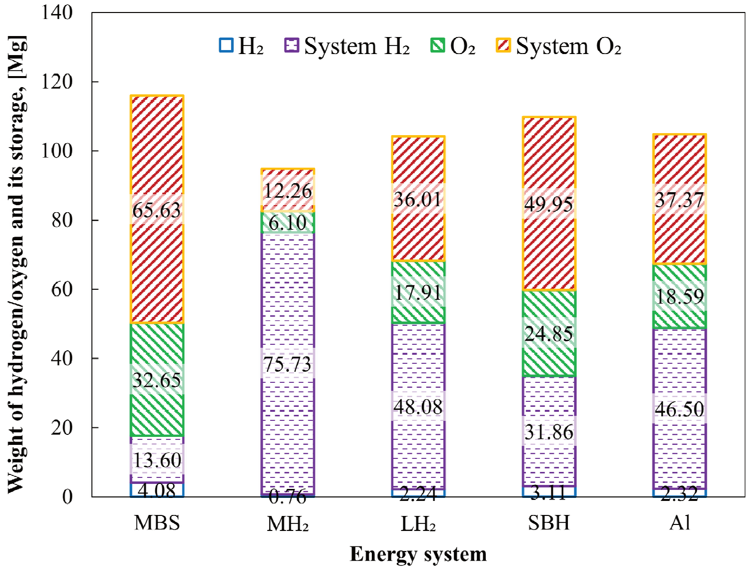

Fig. 5 The weights of hydrogen, oxygen and their storage/generation systems

The achieved submerged endurance and submerged range, depending on submarine speed, while employing only a battery or a combination of battery and fuel cells with various reagent systems are depicted in Figs 6 and 7.

Fig. 6 demonstrates that at an economical speed of 5 knots the submerged endurance will increase by 64.8 times (with MBS) and 12.9 times (with MH_2). At a maximum speed of 18 knots, submerged endurance will boost by 32.1 times (with MBS) and 6.8 times (with MH_2), respectively.

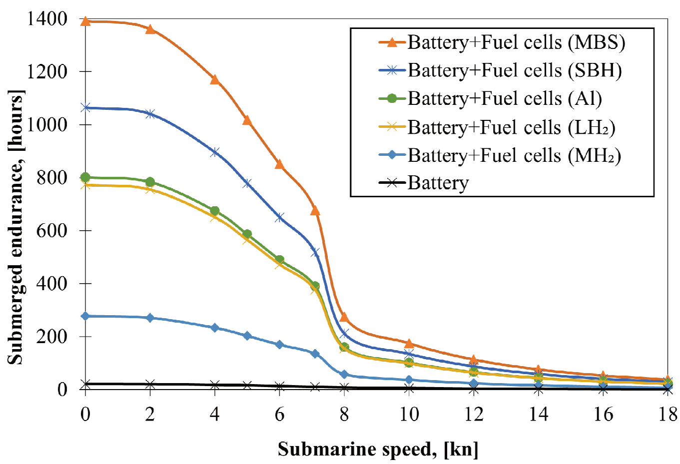

Fig. 6 Dependence of submerged endurance on speed

Fig. 7 shows that the submerged range at the speed of 5 knots increased as much as possible from 79 miles (only BB) to 5 105 miles (BB and PEMFC with MBS), i.e., increased by 64.8 times, and at the maximum speed from 21 miles (only BB) to 684 miles (BB and PEMFC with MBS), i.e., increased by 32.1 times.

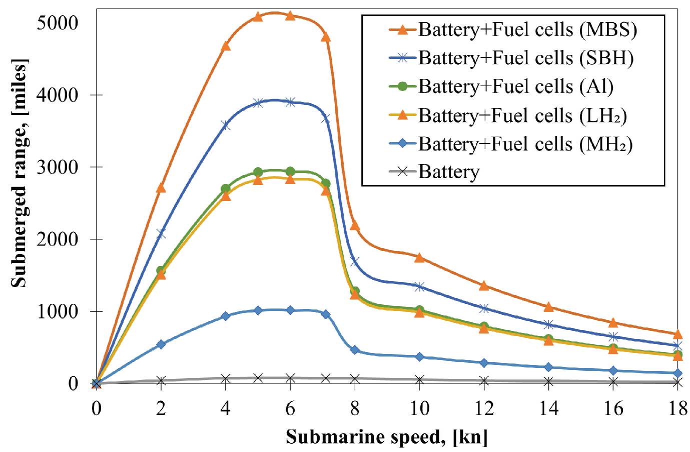

Fig. 7 Dependence of submerged range on speed

Fig. 8 illustrates the indiscretion ratio of diesel-electric propulsion and hybrid AIP based on PEMFC with MBS. The indiscretion ratio when operating diesel generators at all speeds ranges from 0.12 at economical speed to 0.72 at maximum speed. At speeds less than 7.1 knots, the indiscretion ratios for submarines with the hybrid AIP based on PEMFC with MBS are equal to zero; at other speeds, these coefficients range from 0.10 to 0.70 at maximum speed. As a result, AIP improves the stealth of submarines, hence reducing their vulnerability.

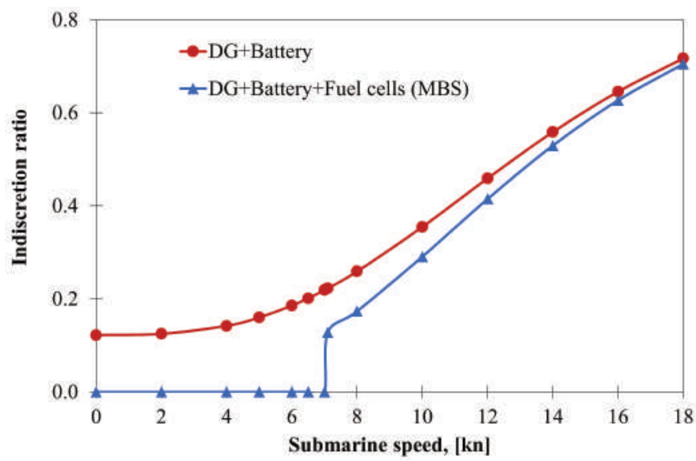

Fig. 8 Dependence of indiscretion ratio on submerged speed

6 Conclusions

This research investigates the hybrid AIP of a small submarine through dividing the daily navigation into 20 hours at an economical speed of 5 knots, 1 hour at a maximum speed of 18 knots, and 3 hours of snorkeling mode for battery charging at a speed of 5 knots. The designed endurances vary based on the reagent storage systems, with a maximum of 33 days and a minimum of 6 days for MBS and MH_2, respectively. MBS has the best option for the hybrid AIP based on PEMFC; SBH placed second when compared to other hydrogen storage/generation systems. Using PEMFC with MBS boosted submerged endurance and range by 32.1 to 64.8 times, as compared to battery-only values. In addition, the indiscretion ratios for submarines with PEMFC and a sailing speed of less than 7.1 knots are zero. They decreased by 2 % compared to conventional diesel-electric submarines operating at other speeds.

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