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ANALYSIS OF FUEL CELL APPLIED FOR SUBMARINE AIR INDEPENDENT PROPULSION (AIP) SYSTEM

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Key words: Air independent propulsion, submerged endurance, fuel cell, submarine.

ABSTRACT

In this paper, the performance of a 2000-ton hybrid AIP system submarine is investigated by analyzing the weight, volume and efficiency of its propulsion system. The engine of the investigated AIP system employs a low temperature polymer electrolyte membrane fuel cell which makes use of the hydrogen and oxygen as the reactants. More specifically, the reactants of fuel cell in this study are considered from the combination of three fuel storage systems, methanol (MeOH), liquid hydrogen (LH_2) and metal hydride (MH_2), and two oxidant storage systems, liquid oxygen (LOX) and compressed oxygen (O_2). Based on the assumed various daily propulsion load consumptions, a propulsion system of a 3500 kW diesel generator, a 300 kW fuel cell, and a 7500 kWh energy capacity Li-ion battery bank is determined.

With the system installed in the submarine, the maximum designed endurance can reach a total of 26 days for the fuel cell using the combination of reactant LH_2 + LOX, and the minimum designed endurance can be up to 10 days for using the reactant $MH_2 + O_2$. For submarine cruising at zero speed, the submerged endurance of the AIP system using reactant LH_2 + LOX plus battery bank is 22.8 times of that using battery bank alone. This value will increase to 25.0 times for submarine cruising at 7.4 knots.

At the cruising speed of 5.5 knots, the maximum submerged range of submarine increases a factor of 24.1 for fuel cell using the reactant of LH_2 + LOX as compared with operation on battery bank alone. Therefore, the submerged endurance is substantial enhanced for using the combination of fuel cell and battery. In addition, the indiscretion ratio is zero for the AIP system submarine with a cruising speed below 7.1 knots; this can greatly reduce the submarine vulnerability. Based on the weight and volume analysis of the submarine equipped with a hybrid AIP system, the usage of the reactant LH_2 + LOX is well suited for a small- to medium-sized 2000-ton submarine with a fuel cell system. Furthermore, using the reactant MeOH + LOX has the advantage for large-sized LT-PEMFC AIP system submarines.

I. INTRODUCTION

Currently most of non-nuclear submarines are propelled by diesel generator and batteries. The generated electric energy from diesel generator is stored in batteries and used to drive the motor of propeller. Due to the need of taking atmosphere air to burn the diesel fuel, the conventional diesel-electric submarine has a time-limit for cruising underwater. The submerged time of a submarine depends on the capacity of battery, and it becomes easy to be discovered either when surfaced or while snorkeling near the surface for recharging its battery. The traditional submarine based on the battery capacity has a maximum submerged time only for a few days. To improve the submerged endurance and reduce its vulnerability, a submarine equipped with an air independent propulsion system is considered to extend the period of patrolling underwater.

The main function of an AIP system is to convert stored reactant energy into electrical energy for the submarine's batteries without surfacing out to get atmosphere air. The AIP systems for conventional submarine can be selected from the following options: Closed Cycle Diesel (CCD), Stirling Engine, Module d'Energie Sous-Marin Autonome (MESMA), Closed Cycle Gas Turbine (CCGT) and low temperature polymer electrolyte membrane fuel cell (LT-PEMFC) (Ghosh and Vasudeva 2011). The use of PEMFC system for an AIP in submarine was initiated in early 1980's. A PEMFC can generate power ranging from a fraction of a watt to hundreds of kilowatts, offering the advantages such as high power density, quick start-up, rapid response to varying load, low operating temperature and zero emission. Sattler discussed the possibility of using fuel cells in submarines for increasing submerged time and reducing noise, vibration and infrared signatures (Sattler 2000). To quick start up and avoid the detection from acoustic signatures, the low temperature polymer electrolyte membrane fuel cell is a favorable choice for a

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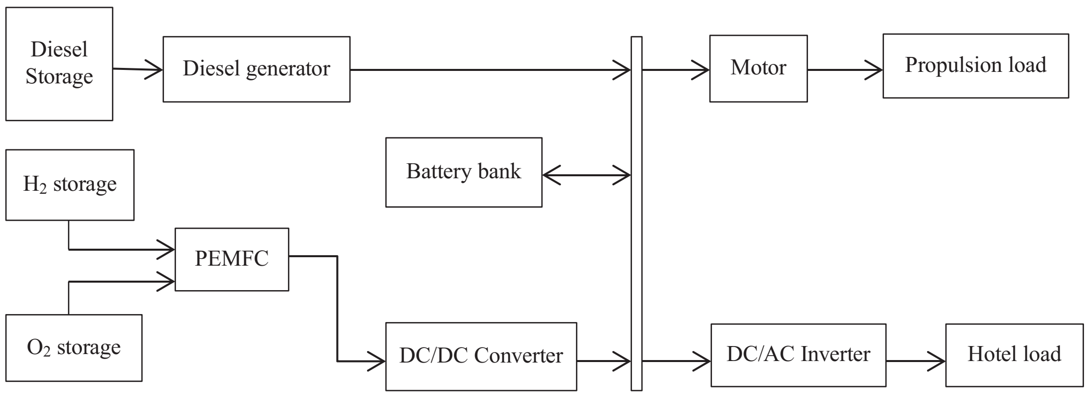

Fig. 1. Schematic representation of a hybrid AIP system of submarines.

submarine AIP system (Brighton, 1994; Psoma, 2002; Virji, 2007).

The LT-PEMFC system developed for submarine consists of the fuel cell stacks and other auxiliary parts (balance of plant, BOP). The BOP frequently makes up a large proportion of the fuel cell system which includes the supply and storage of reactant, power conditioning device and controller. The power conditioning device, DC to AC inverters or DC to DC converters, is used to generate electricity at grid voltage and frequency. The reactant can be stored on board in the form of compressed gas (Montignac et al., 2009), in liquid form at cryogenic temperatures (Weinberger and Lamari, 2009) or in hydride solid form (Sakintuna et al., 2007). The hydrogen stored in hydride form with metals and contained in big storage cylinders is the safest and most conveniently way. However, this storage cylinder is very heavy and huge, and only a limited number of storage cylinders can be carried. Thus the submerged endurance of a submarine with the metal hydride storage for hydrogen is limited.

Although presently the PEMFC system using metal hydride storage and liquid oxygen tanks has been demonstrated and implemented onboard submarines, the PEMFC system with liquid fuel processors for reducing the weight and volume of hydrogen storage remains in the research and development stage (Sterfan and Javier, 2015). The storage of liquid form of hydrogen carrier for diesel or methanol has a better weight percentage compared to other hydrogen storages. The diesel ($C_{13.57}H_{27.14}$) fuels with a relative long carbon chains which can be difficult to process to a hydrogen rich gas. The high sulphur content of diesel fuel is another problem for the Sulphur tolerances requirement of fuel processing equipment and fuel cell. Therefore, diesel fuels are considered to be an inconvenient fuel for fuel cell. Methanol (CH_3OH) is a liquid at ambient temperature and can be used in a direct methanol fuel cell (DMFC) which has poor efficiency. Though the energy density of methanol is significantly lower than diesel fuels, it has no sulfur content and can be reformed easily either in a separated system or integrated in the fuel cell system.

The volume and weight of power plants are critical design aspects for submarine propulsion applications, since volume and weight are commonly restricted for some practical requirements, while a certain amount of power and endurance is required. Depending on the type of power plant application, the submarine designs are typically either volume critical, weight critical, or both. (Brighton et al., 1994) presents conceptual designs for PEMFC based AIP plugs that could be retrofitted to an ocean-going conventional submarine of about 3000-ton displacement. This conventional submarine equipped with a fuel cell based AIP system and retained with the conventional generators and batteries is called hybrid AIP system submarine. Their results show that the submarine's maximum under water range, with sufficient reactants to produce 100 MWh of electric energy, is increased by a factor of almost five compared with operation on batteries alone and its maximum endurance is about 14 days at about 6 knots. (Ghosh and Vasudeva, 2011) analyzed various possible combinations of fuel cell and battery by considering the weight, volume and efficiency of a 3000-ton AIP based submarine. Among different combinations of fuel and oxidant, the MH + LOX system could be simply retrofitted with fuel cell system. However, for MH + O_2, SBH(*sodium borohydride*) + O_2 and SBH + LOX, an extra room of 32 m^3, 186 m^3 and 209 m^3 respectively, has to be created to compensate the deficit of volume. The results also show that the total submerged endurance is enhanced substantially with fuel cell system.

The works described above demonstrates that the AIP system with PEMFC for retrofitting to existing 3000-ton submarines is useful for increasing the range and endurance, and reducing indiscretion time of the bigger sized submarine. In this paper, the performance of a new small- to medium-sized (2000-ton) hybrid AIP system with PEMFC and diesel generator is investigated. The schematic representation with the configuration of the fuel cell reactants from different fuels and oxidants is shown in Fig. 1.

The metal hydride, liquid hydrogen and hydrogen from the reforming of methanol are considered for fuel, and the compressed oxygen and liquid oxygen are considered as oxidant. The designed and submerged endurance of submarine with a hybrid AIP system is investigated for different combination of fuel and oxidant. The indiscretion ratio for submarine using fuel cell and battery is also calculated to verify the reduction of the submarine's vulnerability. Besides, the use of the recommended suitable reactant LH_2 + LOX for a 2000-ton hybrid AIP system submarine can also be demonstrated.

II. POWER REQUIREMENT OF A SUBMARINE

The strategic requirements for submarines to accomplish the tasks generally include the payload necessary for the mission, the maximum depth, the speed, the submerged range and endurance. All of these requirements affect one another; however, the submerged range and endurance are directly related to the required speed and the energy storage which is part of submarine power system. To reach good maneuverability and near maximum underwater range, the cruising speed of a submarine is about 4 to 6 knots. The capacity of a submarine propulsion power system including its energy storage depends on the percentage of the submarine total weight and space available. Typically, the propulsion power systems account for up to 35% of a submarine weight and more than 50% of its space allocation.

The total load required to drive a submerged submarine can be divided into the main propulsion load and the hotel load. Thus, the total power *PW* in (kW) requirement for driving a submerged submarine can be expressed as: (Brighton et al., 1994)

$$PW = \left[(\Delta/22) + 25\right] + 0.0075 \times PW_{fc} + 0.0026 \times \Delta^{2/3} \quad (1)$$

where Δ in (ton) is the submerged displacement of the submarine, PW_{fc} in (kW) the maximum power of the fuel cell, and V in (knot) the submarine velocity. The first term estimates the normal hotel load of the submarine and the second term estimates the addition hotel load due to the fuel cell. These hotel loads include the required power for pumps, blowers, life support systems, communication sets, domestic appliances, control systems and armament. The third term estimates the main propulsion load of a submarine. In Fig. 2, the required total power of a submarine with a maximum power 300 kW fuel cell is plotted as a function of speed and submerged displacement of a submarine.

This study attempts to analyze the submerged range and endurance of a 2000-ton submarine under the following assumptions.

1. The weight of the propulsion power systems is 30% of the total loading weight of the submarine, and the space of the systems is 50% of the space of the submarine.
2. The propulsion load is categorized according to hours of speed required each day.
3. The daily propulsion load is divided into 20 hours for patrolling at 5 knots, 2 hours for sprinting at 18 knots, and the rest of 2 hours for surface sailing at 12 knots respectively.
4. During the 20 hours patrolling, PEMFC supplies the power for the needed load and charges the battery bank simultaneously.
5. During the 2 hours sprinting, the full energy required is supplied by the battery bank.

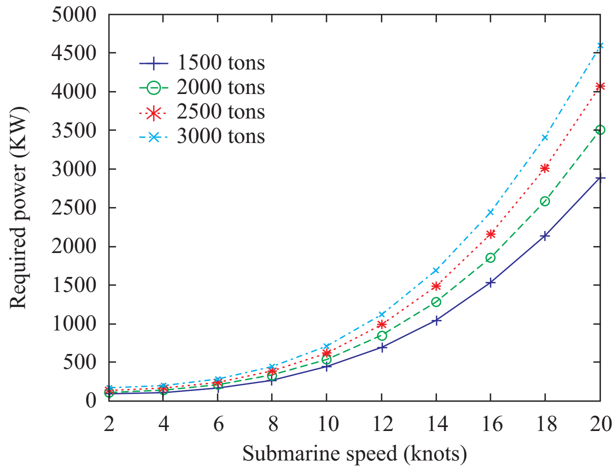

Fig. 2. Required power as a function of submarine speed and submerged displacement.

6. During the 2 hours surface sailing, diesel generator supplies the power for the needed load and charges the battery bank simultaneously.
7. The efficiency of the motor, converter, inverter and battery bank is a constant.

The demanded power output from PEMFC, battery bank and diesel generator can be estimated by using these assumptions.

III. PROPULSION POWER SYSTEM PERFORMANCE

As shown in Fig. 1, the main power of the submarine's hybrid AIP system is supplied by the diesel generator and PEMFC. The power generated from the generator, driven by diesel engine, can be used to drive the motor and charge the battery bank, and the electric power generated from PEMFC can be used for the hotel load and charging the battery bank. Therefore, the electrical power of the battery bank can be charged from the diesel generator or PEMFC, and used for the propulsion and hotel loads. The battery bank capacity PW_{bk} and the diesel generator capacity PW_{dg} are determined from 2 hours sprinting power and 1 hour sprinting required power respectively. The fuel cell capacity PW_{fc} provides the power requirement of patrolling and charging the battery bank to its full capacity at the 20 hours duration.

1. The Weigh and Volume of the Diesel Generator and Fuel Cell System

The weight and space of the diesel generator depend on the weight power density WD_{dg} = 0.05 KW/kg and the volume power density SD_{dg} = 0.04 KW/L respectively (Van Biert et al., 2016). With the efficiency of diesel generator η_{dg} = 40 %, the weight and space of the diesel generator can be expressed as:

$$WT_{dg} = PW_{dg} / (WD_{dg} \times \eta_{dg}) \quad (2)$$

Table 1. Weight and volume power density and efficiency for some equipment.

Equipment \ Property	Weight power density (kW/kg)	Volume power density (kW/L)	Efficiency (%)
Diesel generator	0.05	0.04	40
PEMFC	0.30	0.30	50
Steam reformer	0.10	0.04	80

Table 2. Energy capacity and DOD for two different types of battery.

Battery \ Property	Gravimetric energy capacity (kWh/kg)	Volumetric energy capacity (kWh/L)	Depth of discharge (η_{DOD})
Li-ion battery	0.15	0.20	80
Lead acid battery	0.03	0.06	50

$$SE_{dg} = PW_{dg} /(SD_{dg} \times \eta_{dg}) \tag{3}$$

The weight and space of the PEMFC system can also be calculated by using the weight power density WD_{fc} = 0.30 KW/kg, the volume power density SD_{fc} = 0.30 KW/L, and the efficiency η_{fc} = 50% (Ghosh and Vasudeva, 2011).

$$WT_{fc} = PW_{fc} /(WD_{fc} \times \eta_{fc}) \tag{4}$$

$$SE_{fc} = PW_{fc} /(SD_{fc} \times \eta_{fc}) \tag{5}$$

By using the weight power density WD_{MeOHsr} = 0.10 KW/kg, the volume power density SD_{MeOHsr} = 0.04 KW/L, and the efficiency η_{MeOHsr} = 80 % (Van Biert et al., 2016), the weight and space of the methanol steam reformer are written as:

$$WT_{MeOHsr} = PW_{fc} /(WD_{MeOHsr} \times \eta_{MeOHsr} \times \eta_{fc}) \tag{6}$$

$$SE_{MeOHsr} = PW_{fc} /(SD_{MeOHsr} \times \eta_{MeOHsr} \times \eta_{fc}) \tag{7}$$

Table 1 lists the weight power density, the volume power density, and the efficiency of three propulsion equipment used in the calculation.

2. Battery Bank

Due to the high power-to-energy ratio, a battery bank with good transient capability can be used to compensate for the limited dynamic of the PEMFC system. Therefore, battery is most suitable to cover loads during cold start-up of the PEMFC system and large transients. Li-ion batteries have several advantages over standard submarine lead acids batteries. They have a larger energy density and much lighter weight. They offer approximately 1.3 times capacity for low speed operations and nearly supply up to 3 times capacity for higher speed operations. Li-ion batteries can take very large charging currents over the entire charge range of the battery compared to lead acids, which can only be charged at full rates up to about 85 %, and after that time the charging rate must be reduced to avoid a dangerous gassing situation. The gravimetric energy capacity GC_{bk} and the volumetric energy capacity VC_{bk} is 0.03 kWh/kg and 0.06 kWh/L for lead acids battery, and 0.15 kWh/kg and 0.20 kWh/L for Li-ion battery individually. The depth of discharge η_{DOD} of the lead acids battery and the Li-ion battery is 50% and 80% respectively. The related property of these two battery banks is summarized in Table 2. With the advantages, Li-ion battery is used in this study. The weight and space of its battery bank are shown as:

$$WT_{bk} = PW_{bk} /(GC_{bk} \times \eta_{DOD}) \tag{8}$$

$$SE_{bk} = PW_{bk} /(VC_{bk} \times \eta_{DOD}) \tag{9}$$

3. Storage System (Jensen et al., 2007)

Reactant storage is an important issue for AIP propulsion system since it affects directly on the submerged endurance and the efficiency of the propulsion system. Reactants stored in high pressure gas form, low temperature liquid form and low pressure metal hydride form are considered in this section.

1) Hydrogen

Hydrogen is suitable for PEMFC, as the electrochemical oxidation kinetic is fast, even at low temperature. Thus it can be used without extensive pretreatment. However, the low storage density is the most significant drawback of using hydrogen as a logistic fuel. Compressed hydrogen offers the simplest and least expensive storage solution, and also has the advantage of zero pretreatment. The hydrogen bottle with high pressure up to 700 bar can be made from high strength steel, aluminum or composite fiber. The gravimetric energy densities GD_{H_2} and volumetric energy densities VD_{H_2} of pure hydrogen are 39.5 kWh/kg and 2.2 kWh/L individually. The gravimetric energy densities of compressed hydrogen storage system vary from 1.1 to 1.7 kWh/kg and volumetric energy densities between 0.5 and 0.7 kWh/L. The gravimetric and volumetric energy density for some

Table 3. Comparison of energy densities of different fuel and storage systems.

Fuel and Storage system \ Property	Gravimetric energy density (kWh/kg)	Volumetric energy density (kWh/L)
Pure hydrogen	39.5	2.20
Liquid hydrogen system	2.50	1.20
Metal hydrides system	0.75	1.20
Pure diesel	12.0	10.2
Diesel storage system	8.30	8.20
Pure methanol	6.26	4.90
Methanol storage system	3.90	3.50

fuels and their storage system is summarized in Table 3. The amount of hydrogen required per day in weight WT_{dH_2} and volume SE_{dH_2} is given by:

$$WT_{dH_2} = 20 \times PW_{fc} / (GD_{H_2} \times \eta_{fc}) \tag{10}$$

$$SE_{dH_2} = 20 \times PW_{fc} / (VD_{H_2} \times \eta_{fc}) \tag{11}$$

On the contrary, liquid storage of the hydrogen is more efficient and has the lowest weight and volume. However, it requires low temperature, high cost and greater system complexity. Hydrogen which can be stored under cryogenic state at a temperature less than 20.15 K under ambient pressure, or somewhat higher temperatures and elevated pressures, is referred to as liquid hydrogen (LH_2). The storage tanks for liquid hydrogen are designed to limit the evaporating losses to a tiny amount, typical 0.25 %, per day. Ordinary construction of the tank is a multi-shell flask using an evacuated interstitial space and multilayer insulation to reduce heat transfer through the flask and avoid boiling off the gas. A heat exchanger circulated with the cooling water from PEMFC is required to evaporate the liquid for supply of gas to the fuel cell. The gravimetric energy density GD_{sLH_2} and volumetric energy density VD_{sLH_2} of this storage system have a value of 2.5 kWh/kg and 1.2 kWh/L respectively. The weight WT_{sdLH_2} and volume SE_{sdLH_2} of liquid hydrogen storage system required per day are given by:

$$WT_{sdLH_2} = 20 \times PW_{fc} / (GD_{sLH_2} \times \eta_{fc}) \tag{12}$$

$$SE_{sdLH_2} = 20 \times PW_{fc} / (VD_{sLH_2} \times \eta_{fc}) \tag{13}$$

The daily requirement of the weight WT_{dLH_2} or volume SE_{dLH_2} of liquid hydrogen is the same as the amount of hydrogen required WT_{dH_2} or SE_{dH_2}.

Metal hydrides provide efficient hydrogen storage for various applications, including fuel cell. They are the metal alloys reacting with hydrogen reversibly; they are stored at a low pressure. The hydrogen is liberated from alloys structure by heating the hydride and absorbed to alloys structure by cooling the hydride under pressure. The waste heat from PEMFC is sufficient to heat the hydride. Metal hydride systems have a volumetric energy density VD_{sMH_2} = 1.2 kWh/L and a very low gravimetric energy density GD_{sMH_2} = 0.75 kWh/kg. The hydrogen released rates can be controlled, making it as the safest and most efficient storage option. Due to reversibly absorb and desorb hydrogen with some hysteresis, the metal hydride also loses storage efficiency over multiple cycles. The hydrogen stored in hydride form with alloys is very heavy and huge, only a limited number of storage cylinders can be carried by submarines. Therefore, using this storage always exists a limitation of submerged endurance; however, it is perfectly suitable for a small- to medium-sized submarine. The weight WT_{sdMH_2} and volume SE_{sdMH_2} of metal hydride storage system required per day are given by:

$$WT_{sdMH_2} = 20 \times PW_{fc} / (GD_{sMH_2} \times \eta_{fc}) \tag{14}$$

$$SE_{sdMH_2} = 20 \times PW_{fc} / (VD_{sMH_2} \times \eta_{fc}) \tag{15}$$

Similar to the liquid hydrogen storage system, the daily required hydrogen weight WT_{dMH_2} or volume SE_{dMH_2} for a metal hydride storage system is the same as the amount of hydrogen required per day WT_{dH_2} or SE_{dH_2} in Eq. (10) or (11).

2) Liquid Hydrocarbon Fuel

Generally, pure hydrogen is considered as an ideal fuel of PEMFC system and can be stored in compressed or metal hydride form. However, these storage systems have very low gravimetric and volumetric energy density. As a result, these systems require relatively large space and heavy weight in the submarines. The most common options of hydrogen carrying liquids at ambient temperatures are methanol, ethanol and diesel. Ethanol and diesel require being reformed at high temperatures (above 700°C). The gravimetric energy densities GD_{dsl} and volumetric energy densities VD_{dsl} are 12.0 kWh/kg and 10.2 kWh/L for pure diesel fuel, and GD_{sdsl} = 8.3 kWh/kg and VD_{sdsl} = 8.2 kWh/L for diesel storage system respectively. However, the pure methanol fuel gravimetric and volumetric energy density are GD_{MeOH} = 6.26 kWh/kg and VD_{MeOH} = 4.9 kWh/L, and the methanol fuel storage system gravimetric and volumetric energy densities are $GD_{s\text{MeOH}}$ = 3.9 kWh/kg and $VD_{s\text{MeOH}}$ = 3.5 kWh/L.

Though the energy density of methanol fuel is significantly lower than that of diesel fuel, methanol fuel has the following advantages:

1. Reforming efficiency and H/C ratio of methanol fuel are higher than those of diesel fuel.
2. Methanol fuel can be easily steam reformed at lower temperature (250°C) than that of diesel fuel (higher than 850°C).
3. Total mass and volume of complex reforming equipment can be reduced since methanol fuel has no Sulphur in it.

The amount of diesel storage system required per day in weight WT_{sddsl} and volume SE_{sddsl} is given by:

$$WT_{sddsl} = 2 \times PW_{dg} / (GD_{sdsl} \times \eta_{dg}) \tag{16}$$

$$SE_{sddsl} = 2 \times PW_{dg} / (VD_{sdsl} \times \eta_{dg}) \tag{17}$$

The weight $WT_{s\text{MeOH}}$ and volume $SE_{s\text{MeOH}}$ of methanol fuel storage system required per day are given by:

$$WT_{sdMeOH} = 20 \times PW_{fc} / (GD_{sMeOH} \times \eta_{fc} \times \eta_{MeOHsr}) \tag{18}$$

$$SE_{sdMeOH} = 20 \times PW_{fc} / (VD_{sMeOH} \times \eta_{fc} \times \eta_{MeOHsr}) \tag{19}$$

The weight $WT_{d\text{MeOH}}$ and volume $SE_{d\text{MeOH}}$ of pure methanol fuel required per day can be obtained from Eqs. (18) and (19) by replacing $GD_{s\text{MeOH}}$ and $VD_{s\text{MeOH}}$ with GD_{MeOH} and VD_{MeOH} individually. Reforming can be used to convert hydrocarbon fuels into a mixture of hydrogen and CO_2. The overall reaction of steam reforming methanol fuel is:

$$\mathrm{CH_3OH + H_2O \rightarrow 3H_2 + CO_2}$$

The diesel reformer is less efficient because diesel has a ratio of hydrogen to carbon only two to one, whereas methanol has the ratio of four to one. The high temperature diesel reformer also requires a longer start-up time than methanol reformer. Sulphur purifier at the reformer output needs a considerable space as big as the reformer. The methanol is mixed with water, heated, evaporated and finally fed to the steam reformer. The water mixed with methanol is from the production of the fuel cell. The heat to supply the reaction can be obtained by burning methanol or unused hydrogen with oxygen from compressed or liquid oxygen. To prevent poisoning of the platinum catalyst in the fuel cell electrodes, small amount of CO produced in the reforming process must be removed from the reformate by means of gas purification unit based on hydrogen—permeable membranes (Krummrich and Llabres, 2015). CO_2 produced from the reforming reaction cannot be stored on board because it requires a lot of space and heavy pressure containers. It must be discharged into the surrounding sea. The lost weight of CO_2 must be compensated with sea water to ensure a balance in the weight system. The weight of CO_2 produced per day can be calculated by the equation:

$$WT_{d\mathrm{CO_2}} = (44/32) \times 20 \times PW_{fc} / (GD_{MeOH} \times \eta_{fc} \times \eta_{MeOHsr}) \tag{20}$$

3) Oxygen Storage

The chemical products from the fuel cell AIP system are water (H_2O) and carbon dioxide (CO_2). Therefore, the ratio of hydrogen to carbon in the hydrocarbon fuel structure should be high, because the oxidation of C requires more oxygen than that of H. The oxidant of PEMFC can be oxygen or air. The air with lower amount of oxygen needs a bulky storage system and is not considered as the sources of oxygen in submarine. In this study, compressed oxygen at 700 bar and cryogenic liquid oxygen (LOX) are used for investigation. The gravimetric and volumetric fraction of the compressed oxygen storage system are $GF_{s\mathrm{O_2}}$ = 0.265 and $VF_{s\mathrm{O_2}}$ = 0.20 individually (Ghosh and Vasudeva 2011). The cryogenic liquid oxygen tank is the dominant component for deciding the AIP system size. The boiling point of oxygen is -283°C, and the boiling losses when refueling and during the storage period must be considered. The gravimetric and volumetric density of the cryogenic liquid oxygen storage system are $GF_{s\text{LOX}}$ = 0.61 and $VF_{s\text{LOX}}$ = 0.35 respectively. The daily weight required of the oxygen is eight times of the daily weight required of the hydrogen. For the fuel of compressed hydrogen and metal hydride, the weight and volume of cryogenic liquid oxygen system required per day are expressed as:

$$WT_{sdLOXH_2} = 8 \times WT_{dH_2} / GF_{sLOX} \tag{21}$$

$$SE_{sdLOXH_2} = 8 \times WT_{dH_2} / \rho_{O_2} / VF_{sLOX} \tag{22}$$

The daily weight required of the oxygen is one and half times of daily weight required of the methanol. The weight and volume of cryogenic liquid oxygen system required per day for methanol fuel are expressed as:

$$WT_{sdLOXMeOH} = 1.5 \times 20 \times PW_{fc} / (GD_{MeOH} \times \eta_{fc} \times \eta_{MeOHsr}) / GF_{sLOX} \tag{23}$$

$$SE_{sdLOXMeOH} = 1.5 \times 20 \times PW_{fc} / (GD_{MeOH} \times \eta_{fc} \times \eta_{MeOHsr}) / \rho_{O_2} / VF_{sLOX} \tag{24}$$

Where ρ_{O_2} is the density of cryogenic liquid oxygen, and the value is equal to 1.141 kg/m^3. Both weights, $WT_{sd\mathrm{O_2H_2}}$ and $WT_{sd\mathrm{O_2MeOH}}$, of the compressed oxygen system required per day can be calculated from Eqs. (21) and (23) by replacing $GF_{s\text{LOX}}$ with $GF_{s\mathrm{O_2}}$. Both volumes, $SE_{sd\mathrm{O_2H_2}}$ and $SE_{sd\mathrm{O_2MeOH}}$,

Table 4. Gravimetric and volumetric fraction for oxygen storage system. (Ghosh and Vasudeva 2011).

Oxygen storage system	Gravimetric fraction	Volumetric fraction
Liquid oxygen	0.61	0.35
Compressed oxygen	0.265	0.20

of the compressed oxygen system required per day can be written as:

$$SE_{sdO_2H_2} = 8 \times WT_{dH_2} \times 22.4 \times 10^3 / (M_{O_2} \times P_{O_2}) / VF_{sO_2} \quad (25)$$

$$SE_{sd\mathrm{O_2MeOH}} = 1.5 \times WT_{sd\mathrm{MeOH}} \times (GD_{s\mathrm{MeOH}} / GD_{\mathrm{MeOH}}) \times 22.4 \times 10^3 / (M_{\mathrm{O_2}} \times P_{\mathrm{O_2}}) / VF_{s\mathrm{O_2}} \quad (26)$$

where $M_{\mathrm{O_2}}$ is the molecular weight of oxygen in (kg/mole), and $P_{\mathrm{O_2}}$ is the oxygen tank pressure in (bar). The influence of temperature is neglected in Eqs. (25) and (26). Table 4 lists the gravimetric and volumetric fraction of the oxygen storage system.

4. Designed Endurance

The designed endurance of a submarine refers to the duration that the submarine can sail using the assumed daily propulsion load. This is related to the total weight or total volume of fuel and oxidant which can be stored in the submarine. The total weight and volume of the hybrid AIP system equipment is written as:

$$WT_{AIPsystem} = WT_{dg} + WT_{fc} + WT_{bk} + WT_{\mathrm{MeOH}sr} \quad (27)$$

$$SE_{AIPsystem} = SE_{dg} + SE_{fc} + SE_{bk} + SE_{\mathrm{MeOH}sr} \quad (28)$$

If the reactants of the fuel cell are liquid hydrogen (LH_2) and cryogenic liquid oxygen (LOX), the daily required weight and volume of the reactants for the hotel and propulsion load can be written as:

$$WT_{sd\mathrm{LH_2}/s\mathrm{LOX}} = WT_{sd\mathrm{LH_2}} + WT_{sd\mathrm{LOXH_2}} \quad (29)$$

$$SE_{sd\mathrm{LH_2}/s\mathrm{LOX}} = SE_{sd\mathrm{LH_2}} + SE_{sd\mathrm{LOXH_2}} \quad (30)$$

The designed endurance in days, estimated from the weight and volume analysis for the fuel cell using liquid hydrogen and cryogenic liquid oxygen, can be written as:

$$DEW_{sd\mathrm{LH_2}/s\mathrm{LOX}} = (0.3 \times \Delta \times (1 - 0.15) - WT_{AIPsystem}) / WT_{sd\mathrm{LH_2}/s\mathrm{LOX}} \quad (31)$$

$$DEV_{sd\mathrm{LH_2}/s\mathrm{LOX}} = (0.5 \times \nabla \times (1 - 0.15) - SE_{AIPsystem}) / SE_{sd\mathrm{LH_2}/s\mathrm{LOX}} \quad (32)$$

where ∇ in (m^3) is the total internal volume of a submarine and the displacement $\Delta = \rho_s \times \nabla$, ρ_s is the density of sea water. Eqs. (31) and (32) have an assumption that the submarine floating on the water surface has a 15% of its whole volume protruding out of the water surface. Except the capacity used for the water ballast in the submarine, the weight of the propulsion system is assumed to be 30% of its total available loading weight, and the volume is assumed to be 50% of its total available loading volume. Similarly, the designed endurance measured in days for the fuel cell using reactants from the combination of other fuels and oxidant can be found in the same manner.

5. Submerged Endurance

The submerged endurance is the duration for which the submarine can sail without accessing atmospheric air. It depends on the total fuel stored in the submarine and used for the fuel cell system. The submerged endurance in hours based on available weight and volume of the fuel cell reactants, liquid hydrogen and cryogenic liquid oxygen, can be calculated from the following equations:

$$SEW_{s\mathrm{LH_2}/s\mathrm{LOX}} = (WT_{d\mathrm{LH_2}} \times DEW_{sd\mathrm{LH_2}/s\mathrm{LOX}}) / (PW_{sail} / GD_{\mathrm{LH_2}}) \quad (33)$$

$$SEV_{s\mathrm{LH_2}/s\mathrm{LOX}} = (SE_{d\mathrm{LH_2}} \times DEV_{sd\mathrm{LH_2}/s\mathrm{LOX}}) / (PW_{sail} / VD_{\mathrm{LH_2}}) \quad (34)$$

where PW_{sail} is the required power for submarine with a specified sailing speed in the underwater. The submerged endurance for the fuel cell using the other reactants can also be calculated in the same way.

6. Indiscretion Ratio

The indiscretion ratio is the fraction of time that a submarine spends snorkeling to maintain the state of charge of the battery and can be expressed as: (Brighton et al., 1994)

$$I_r = t_s / (t_s + t_b) \quad (35)$$

where t_s is the time spent snorkeling to recharge the battery to its original state of charge, and t_b is the time spent discharging the battery. The vulnerability of the submarine can be reduced by reducing the indiscretion ratio.

IV. RESULTS AND DISCUSSIONS

This study investigates the submerged endurance of a 2000-ton submarine equipped with a hybrid AIP system by using the weight and volume analysis of the submarine. The main engine of the AIP system used for the submarine is a LT-PEMFC. It is

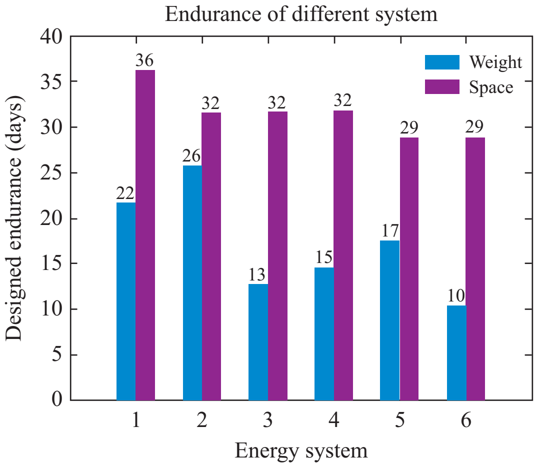

Fig. 3. The designed endurance of a submarine with different energy system. (Energy system 1: MeOH + LOX, 2: LH_2 + LOX, 3: MH_2 + LOX, 4: MeOH + O_2, 5: LH_2 + O_2, 6: MH_2 + O_2).

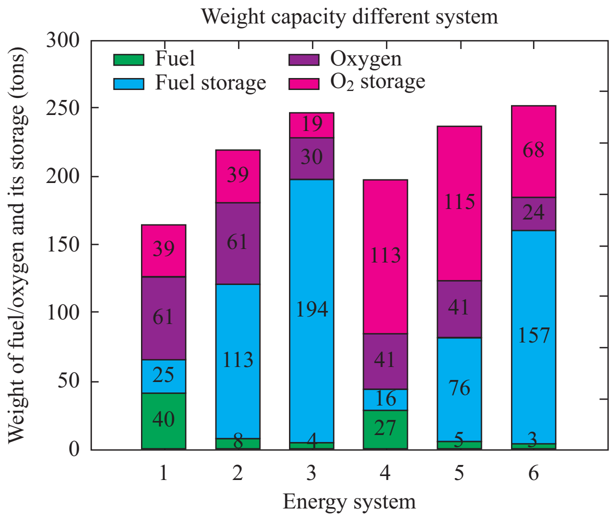

Fig. 4. Weight comparison between the different reactants and storage system. (Energy system 1: MeOH + LOX, 2: LH_2 + LOX, 3: MH_2 + LOX, 4: MeOH + O_2, 5: LH_2 + O_2, 6: MH_2 + O_2).

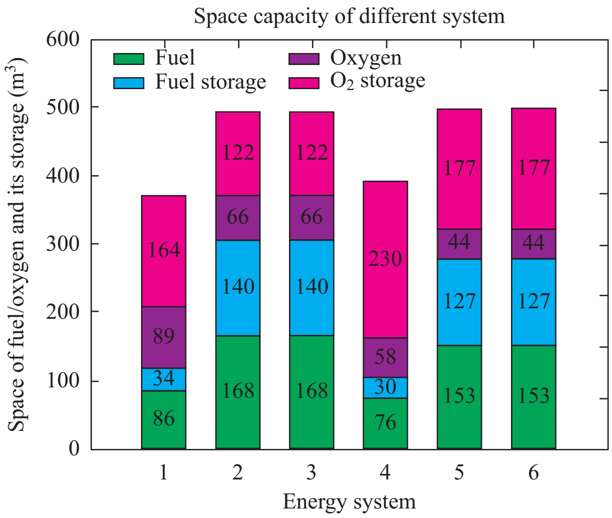

Fig. 5. Volume comparison among different reactants and storage systems. (Energy system 1: MeOH + LOX, 2: LH_2 + LOX, 3: MH_2 + LOX, 4: MeOH + O_2, 5: LH_2 + O_2, 6: MH_2 + O_2).

assumed that the submarine floating on the water surface has a 15% of its whole volume protruding out of the water surface. Hence for the capacity of the propulsion system, a weight of 510-ton is estimated as 30% of the total available loading weight, and a volume of 830 m^3 is considered as 50% of the total available loading volume of the submarine, excluding the weight and volume used for water ballast. The propulsion system includes the diesel generator, fuel cell, battery bank, fuels and oxygen storage. A 3500 kW diesel generator and a 300 kW fuel cell are determined from the daily propulsion load required. The Li-ion battery bank with DOD 80% and efficiency 90% shall have 7500 kWh energy capacity to meet the requirement of 20 hours patrolling at 5 knots. The endurance of the submarine which depends on its carrying capacity of fuel and oxygen can be estimated in the paper. Fig. 3 shows the designed endurance of a submarine with fuel cell using different fuel and oxygen system.

The number in the abscissa in Fig. 3 represents six different energy systems which have a combination of fuel and oxygen storage system. The oxidant of energy systems 1 to 3 is cryogenic liquid oxygen (LOX); the oxidant of systems 4 to 6 is compressed oxygen (O_2). The fuel of energy systems 1 and 4 is methanol which can be reformed to produce hydrogen. The liquid hydrogen is used as fuel in energy systems 2 and 5, and metal hydrides are used in energy systems 3 and 6. Therefore, the reactants of energy systems 1 to 6 can be simply expressed as MeOH + LOX, LH_2 + LOX, MH_2 + LOX, MeOH + O_2, LH_2 + O_2 and MH_2 + O_2 respectively. The ordinate in Fig. 3 shows the designed endurance for the submarine sailing at assumed daily propulsion load. As shown in the figure, the designed endurance calculated by using the volume analysis is larger than the endurance calculated by the weight analysis. Hence the designed endurance of the submarine is constrained by the weight of the AIP system. The submarine using the energy system of liquid hydrogen and liquid oxygen has the maximum designed endurance for 26 days. On the contrary, for the same total 510-ton weight propulsion system, the submarine energy system using the metal hydride and compressed oxygen has the minimum designed endurance for 10 days only.

In Fig. 4 and Fig. 5, the weight and volume of fuel, oxidant and their storage containers are compared for the six different energy systems. The abscissa of these figures presents the same fuel and oxygen combination system as in the abscissa of Fig. 3. In Fig. 4 and Fig. 5, the number in the middle of each stacked bar graph expresses the weight and the volume individually. For example, in Fig. 4, the number of 157 in the middle of blue color bar at energy system 6 indicates the weight is 157 tons for the metal hydride storage container. In Fig. 5, the number of 89 in the middle of purple color bar at energy system 1 represents the volume is 89 m^3 for the required liquid oxygen.

The weight and volume of the fuel and oxidant storage container are calculated by using the gravimetric and volumetric energy density. For each kind of fuel, the required weight and volume of compressed oxygen storage container (pink segment in energy system 4 to 6) are greater than those of corresponding liquid oxygen storage tanks (pink segment in energy system 1 to 3). Therefore, the amount of oxygen stored in the compressed oxygen storage container is less than that stored in liquid oxygen storage tank from both of weight and volume analysis, as shown in Figs. 4 and 5. Since the oxygen consumption is very important for the AIP system, liquid oxygen storage system should be used in this 2000-ton (small- to medium-sized) submarine.

From Fig. 4, the total weight of these three fuel systems, methanol, liquid hydrogen, and metal hydride, is 165, 221 and 247 individually. Apparently, methanol is the lowest in the three systems using the same oxidant LOX. Therefore, the total weight of the AIP equipment (diesel generator, fuel cell, battery bank and auxiliary systems) using methanol fuel is heavier than that of AIP equipment using the other two fuel systems. This is resulted from an extra weight required for a reformer of the methanol system. The same result can also be found in Fig. 5 for the space analysis. The reformer must be operated with fuel, oxygen and water to convert the methanol to hydrogen and carbon dioxide. The produced carbon dioxide, 2.56 ton per day, is compressed and discharged from the submarine, and the same weight of ballast sea water should be taken on board. The weight and volume of the produced water and ballast water are not included in Fig. 4 and Fig. 5 respectively.

The 8-ton hydrogen stored in liquid storage is much higher than the 4-ton hydrogen stored in metal hydride, as shown in Fig. 4. Therefore, the combination of liquid hydrogen with liquid oxygen is suited for 2000-ton, small- to medium-sized, submarines with LT-PEMFC AIP system. On the other hand, the reformer requires extra weight and space to install; thus the methanol fuel and liquid oxygen system can be applied to bigger sized AIP system submarines.

The submerged endurance as a function of the submarine speed is plotted in Fig. 6. The curves for fuel cell using two different energy systems, MeOH + LOX and LH_2 + LOX plus battery bank, have a cusp at 7.4 knots. At this speed, the usage of the battery bank and the reactants of fuel cell are completely exhausted at the same time. For speed greater than 7.4 knots, the fuel cell will still have reactants available after the battery bank is completely exhausted. The submerged endurance of the submarine using battery bank alone at a speed of 5 knots is only 34.3 hours. For submarine cruising at zero speed, the submerged endurance of the AIP system using reactant LH_2 + LOX plus battery bank is 22.8 times of that using battery bank alone. This value will increase to 25.0 times for submarine cruising at 7.4 knots. However, the ratio rapidly decreases to 1.12 at a higher speed of 18 knots due to not using all of the fuel cell reactants. This phenomenon can be adjusted by increasing battery bank capacity to obtain greater submerged endurance at high speed without losing low speed submerged endurance.

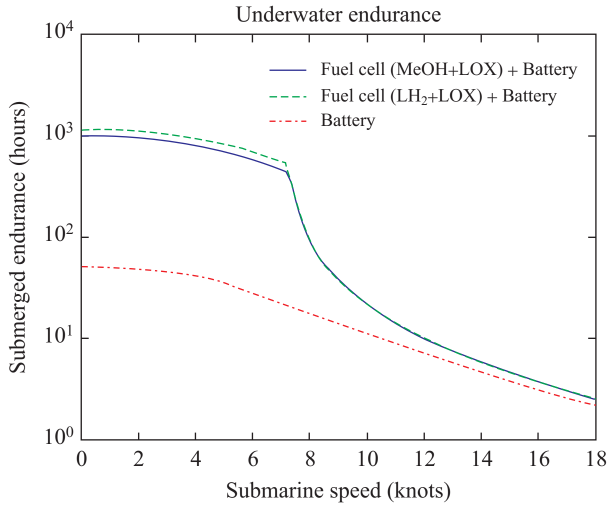

Fig. 6. Submerged range in (hours) as a function of submarine speed for using two energy system fuel cell plus battery and for using battery alone.

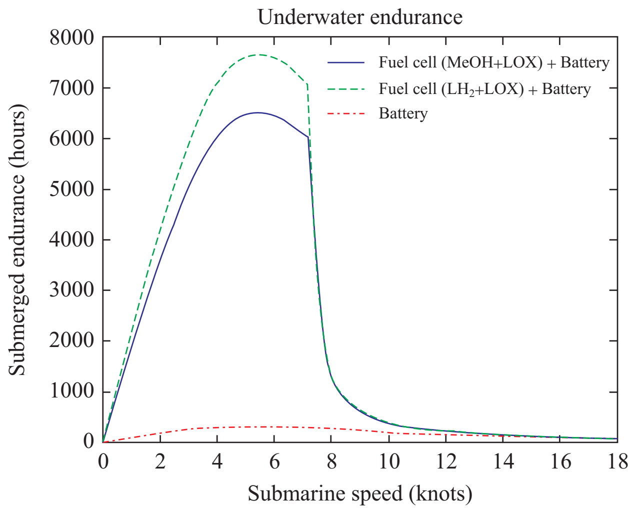

Fig. 7. Submerged range in (km) as a function of submarine speed for using two energy system fuel cell plus battery and for using battery alone.

The submerged range as a function of speed for the submarine operating on battery bank alone and fuel cell plus battery bank is shown in Fig. 7. The max submerged range of the submarine using the battery bank alone is only 318 km at a speed of 5.5 knots. However a 300 kW fuel cell using two energy systems, MeOH + LOX and LH_2 + LOX, plus battery bank can reach the max submerged range about 6515 km and 7670 km individually at the same speed of 5.5 knots. Therefore, the underwater performance of the 2000-ton submarine can be significantly enhanced by using LT-PEMFC AIP system. In Fig. 7 the two curves of fuel cell plus battery bank also have a cusp at the speed of 7.4 knots. There is a sharp drop in submerged range for speed higher than 7.4 knots. In this situation, the battery bank will be exhausted but the fuel cell will still have re-

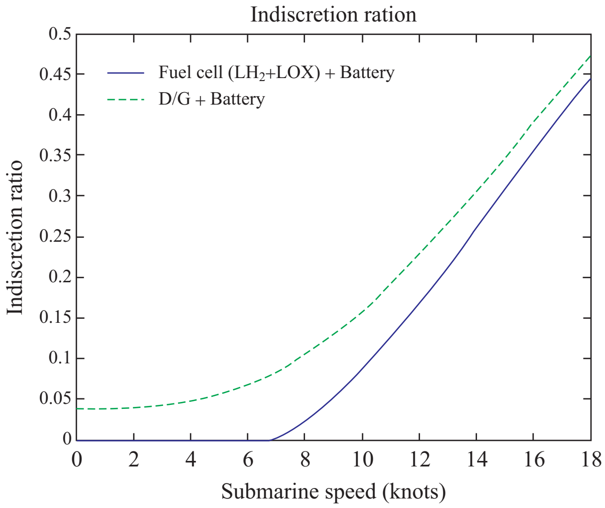

Fig. 8. Indiscretion ratio as a function of submarine speed for using fuel cell plus battery and for using the battery plus diesel generator.

actants available.

The indiscretion ratio as a function of the submarine speed for using LH_2 + LOX energy system fuel cell plus battery and for the battery plus diesel generator is calculated and shown in Fig. 8. For the battery plus diesel generator system, the indiscretion ratio increases from a minimum about 4% at low speed to 47% at 18 knots. However, the indiscretion ratio stays at zero for speed up to about 7.1 knots for fuel cell plus battery. Therefore, the use of LT-PEMFC AIP greatly reduces the indiscretion ratio of submarine and hence reduces its vulnerability.

V. CONCLUSIONS

The analysis technique for weight, volume and efficiency of the AIP system is applicable to investigate the performance of a 2000-ton hybrid AIP system submarine. The reactants of LT-PEMFC AIP system are the combination from three fuel storage systems, methanol, liquid hydrogen and metal hydride, and two oxidant storage systems, liquid oxygen and compressed oxygen. The available weight of 510-ton and the volume of 830 m^3 of the hybrid AIP system are assumed as 30% of the total weight and 50% of the total space of the 2000-ton submarine, except the ballast water. The daily propulsion load requirements, 20 hours for patrolling at 5 knots, 2 hours for sprinting at 18 knots and 2 hours for surface sailing at 12 knots, are assumed to determine the power of diesel generator to be 3500 kW, fuel cell to be 300 kW and the capacity of Li-ion battery bank to be 7500 kWh. Several conclusions can be drawn as follows:

1. The designed endurance of the submarine is limited by the weight of AIP system. The maximum designed endurance is 26 days for fuel cell using liquid hydrogen and liquid oxygen, and the minimum designed endurance is 10 days for using metal hydride and compressed oxygen.
2. The 2000-ton, small- to medium-sized, submarine with LT-PEMFC AIP system using the reactants of liquid hydrogen and liquid oxygen has higher endurance performance compared to the use of other reactants. Due to the conversion of the methanol fuel to hydrogen for fuel cell usage, the AIP system requires additional weight and volume for the reformer. Hence the fuel cell using the methanol fuel is only suggested for bigger-sized AIP system submarines.
3. The ratio of submerged endurance between fuel cell using 8-ton liquid hydrogen and 61-ton oxygen plus battery bank and battery bank alone increases from 22.8 to 25.0 corresponds to the speed increased from zero to 7.4 knots. On the other hand, the maximum submerged range of submarine using fuel cell plus battery bank could be increased by a factor of 24.1 at speed 5.5 knots compared with operation on battery bank alone. Therefore, the submerged endurance is substantial enhanced for the AIP system with fuel cell and battery used together.
4. The indiscretion ratio is zero at speed below 7.1 knots for submarine using LT-PEMFC AIP system; this can greatly reduce the submarine's vulnerability.

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