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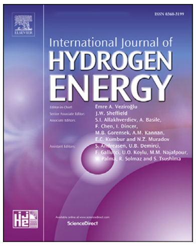

Fuel cell systems for long-endurance autonomous underwater vehicles – challenges and benefits

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A B S T R A C T

Autonomous underwater vehicles (AUVs) are programmable, robotic vehicles that can drift, drive, or glide through the ocean without real-time control by human operators. AUVs that also can follow a planned trajectory with a chosen depth profile are used for geophysical surveys, subsea pipeline inspection, marine archaeology, and more. Most AUVs are followed by a mother ship that adds significantly to the cost of an AUV mission. One pathway to reduce this need is to develop long-endurance AUVs by improving navigation, autonomy and energy storage. Long-endurance AUVs can open up for more challenging mission types than what is possible today. Fuel cell systems are a key technology for increasing the endurance of AUVs beyond the capability of batteries. However, several challenges exist for underwater operation of fuel cell systems. These are related to storage or generation of hydrogen and oxygen, buoyancy and trim, and the demanding environment of the ambient seawater. Protecting the fuel cell inside a sealed container brings along more challenges related to condensation, cooling and accumulation of inert gases or reactants. This paper elaborates on these technical challenges and describes the solutions that the Norwegian Defence Research Establishment (FFI) has chosen in its development of a fuel cell system for long-endurance AUVs. The reported solutions enabled a 24 h demonstration of FFI's fuel cell system under water. The remaining work towards a prototype sea trial is outlined.

Introduction

Autonomous underwater vehicles (AUVs) are programmable, robotic vehicles that, depending on their design, can drift, drive, or glide through the ocean without real-time control by human operators [1]. In this paper we will limit our discussion to AUVs that can follow a planned trajectory with a chosen depth profile, thus excluding gliders. AUVs are used for geophysical surveys, subsea pipeline inspection, environmental monitoring, marine archaeology and search for lost assets, to name a few examples. They are expected to play an even more important role in the future, for example within deep sea mining, subsea oil and gas installations and large scale subsea surveys [2].

State-of-the-art commercially available AUVs have an endurance of more than 70 h and near 220 nautical miles

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range with all sensors operating [3,4]. Most AUVs are followed by a mother ship that aids with navigation and in-mission decision-making. After each mission, the AUV must be recovered by the mother ship or connect to a docking system for recharging and downloading of harvested data. Manned mother ships have high day rates and add significantly to the cost of an AUV mission. As an example, the day rate for a research vessel from Marine Institute in Ireland is € 19 000 for non-commercial missions [5].

Developing long-endurance AUVs is one possible pathway to reduce the need for an expensive mother ship. A long-endurance AUV requires further improvements within autonomy, navigation and energy storage. With these improvements in place, the AUV can be launched and operate independently for its full endurance, also in unknown waters. In the meantime, the mother ship can be liberated to solve other tasks or launch AUVs in other areas. With today's level of AUV autonomy, this operation would introduce a risk of losing the AUV [6]. For many AUV users, this is an unviable option, and they therefore choose to follow the AUV with a mother ship.

Extending the AUV endurance to several weeks or even months could open up for more challenging mission types such as under ice seabed surveys, long-distance ocean current monitoring at constant depth, fish shoal tracking and ultra-long pipeline inspection. The need for a mother ship could be eliminated altogether if the range of the AUV is sufficiently high to be launched from pier. This paper addresses the energy storage issue, which is one of the crucial improvement areas for achieving a long-endurance AUV.

Most commercial AUVs today are powered by batteries [7]. Fuel cell systems have the potential to increase AUV endurance beyond what batteries can provide [8–10]. In a fuel cell, the chemical energy stored in its reactants is converted to electrical energy by an electrochemical process [11]. Unlike batteries, the reactants are continuously supplied from external storage media. The fuel cell and auxiliaries are dimensioned to match the power demand of the application, while the external storage media are dimensioned to match the energy demand. Since the energy density of the storage media is much higher than for batteries, fuel cell systems have the potential to outperform the energy density of batteries. However, the fuel cell and auxiliaries add to the weight and volume of the total system, reducing the advantage, especially for lightweight and man-portable AUVs.

Fuel cell systems for AUVs were reviewed by Mendez et al., in 2014 [12]. German [13–16], Japanese [17–19], French [20], and US teams [21] have developed fuel cell systems for AUVs. The Japanese AUV Urashima dived down to 1507 m powered by a fuel cell system in 2003 and achieved a cruising distance of 317 km in 2005 [17]. The fuel cell system in Urashima is based on a proton exchange membrane (PEM) fuel cell with hydrogen stored in a metal hydride container and oxygen in a pressure tank. The fuel cell system was later improved and passed subsequent sea trials [19]. The French team carried out several dives down to maximum 400 m depth with their fuel cell system on board the IDEF^x AUV in 2009 [20]. This system used PEM fuel cells with hydrogen and oxygen stored in pressure tanks. The US Office of Naval Research awarded several contracts in 2011–2012 to develop fuel cell systems for a large displacement unmanned underwater vehicle (LDUUV) [21]. One of these contracts resulted in a successful demonstration in an AUV in 2015, and General Atomics completed a 46-day demonstration of their Aluminium Power System in 2018 [22]. The latter system uses hydrogen generated by the reaction between aluminium and water while oxygen is stored in gaseous or liquid form. Results from the other US development efforts have barely been reported in the open literature, but in 2018, the U.S. Navy planned to accelerate its acquisition strategies for LDUUVs [23]. Other new initiatives within fuel cells for AUVs are undertaken by Jalvasub Engineering with their Hycogen unit [24] and thyssenkrupp Marine Systems with partners in the Large Modifiable Underwater Mothership project [25].

Fuel cell systems have been operating for several years on the submarine class 212A and 214 [26]. The boundary conditions for a submarine fuel cell are of course very different from AUVs. Another underwater application of fuel cells is the diver operated underwater vehicle developed by Shih and coworkers [27,28]. Teledyne Energy Systems promotes an untethered subsea power node based on fuel cells and compressed gas reactant storage [29].

Despite their performance advantage, fuel cells for AUVs have yet to become a commercial success. One reason is high system complexity compared to batteries. This means more extensive maintenance routines and more possibilities for failure. Refuelling of a fuel cell system entails handling of highly reactive, and often expensive, chemicals. In comparison, the ease of operation and simple recharging interfaces of batteries are often highly valued by the users. Additionally, fuel cells for AUVs are a fairly novel technology, which entails high development cost [12]. This is a major barrier for the introduction of fuel cell AUVs on the commercial market.

The Norwegian Defence Research Establishment (FFI) has worked with AUVs since the early 1990s and has developed several power supply systems for AUVs in cooperation with Kongsberg Maritime: a magnesium-seawater battery [30], an aluminium-hydrogen peroxide (Al/H_2O_2) semi fuel cell [31] and a pressure tolerant Li-ion battery [32]. The Al/H_2O_2 semi fuel cell was in commercial operation between 1998 and 2017 in the HUGIN II, 3000 and 4500 AUV. To our knowledge, it still holds the world record in commercial AUV endurance at depths more than 3000 m [33]. The pressure tolerant Li-ion battery was first operated in the HUGIN 1000 in 2004 and is still powering the HUGIN AUVs of Kongsberg Maritime.

As a natural next step in the development of AUV power supply systems, FFI built a fuel cell system for AUVs in the period 2005–2014 [34]. This system builds on our experience with hydrogen peroxide from the Al/H_2O_2 semi fuel cell. The development culminated with a 24 h demonstration in a sealed container under water.

In this paper, we elaborate on the technical challenges that arise when operating a fuel cell system under water without access to ambient air. The practical solutions that FFI has chosen for these challenges are described. We present an overview of the fuel cell system developed at FFI and outline the remaining work towards a prototype sea trial.

Challenges for underwater operation of fuel cells

Challenges related to land-based operation of fuel cell systems, in applications such as cars, fork lifts and trains have for the most part been solved. For fuel cell systems that shall operate under water, several challenges are added to the list. These include hydrogen and oxygen storage or generation, buoyancy and trim, ambient conditions and other challenges that stem from operation of fuel cells in a sealed container.

The PEM fuel cell technology has been chosen for most fuel cell AUV applications [12]. Even though alternatives exist, we will limit our discussion to PEM fuel cells.

Hydrogen storage/generation: In most applications PEM fuel cells operate on pure hydrogen. Due to the physical properties of hydrogen, compact hydrogen storage is difficult to achieve also on land-based applications. Under water, additional challenges arise from the ambient seawater conditions. The depth rating of the AUV determines the ambient pressure that the equipment must sustain, and this parameter heavily affects which hydrogen storage/generation method that is most feasible.

Several methods to store or generate hydrogen exist and have been reviewed elsewhere [8,12,35–37]. Table 1 gives a summary of alternatives with our evaluated ranking of their properties for underwater use. The ranking is not absolute, but is one way of comparing the alternatives in a qualitative way. Several candidates have high gravimetric and volumetric energy density. However, when compensating for their buoyancy and buoyancy change throughout the mission, they become less attractive. This is further discussed in the buoyancy section below. In addition to the energy density at neutral buoyancy, the system simplicity and depth independence are important factors for underwater applications. System simplicity contains aspects such as balance-of-plant (BOP) complexity, efforts required to implement the technology on an AUV, how easy the reaction by-products can be managed, etc. Depth independence reflects to what extent the energy density decreases with depth rating. The ranking has been given for an AUV size and depth rating equivalent to the LDUUV specification [38]. Note that the ranking may change with size and depth rating. For instance, large AUVs will favour liquid hydrogen, since the insulation to hydrogen ratio of the liquid hydrogen tank decreases with size. Also, reformer based systems will be favoured by large AUVs since the volume and weight of BOP components will be small compared to the energy storage medium at high energy demands. Since the ranking of the properties is based on a qualitative assessment and may change with vessel and mission type, the alternatives are not given an overall ranking.

Oxygen storage/generation: Seawater typically contains 3–7 ml dissolved oxygen per liter [39]. Low-power seawater batteries, such as the Mg-seawater battery [30], uses this oxygen to generate power, but the concentration is too low to sustain the power needed for propulsion and payload on an AUV. Therefore oxygen must be stored or generated on board the AUV. This brings along a huge weight and volume penalty to the fuel cell system. Oxygen weighs eight times more than the equivalent amount of hydrogen needed for the fuel cell reaction. This reduces the energy density advantage of fuel cells greatly compared to land-based applications. Also the equipment needed to store or generate oxygen reduces the energy density. The equipment must sustain ambient conditions, and the depth rating greatly affects which oxygen storage/generation method that is most feasible.

Several oxygen storage/generation candidates exist and have been reviewed elsewhere [8,12,36]. Table 2 gives a summary of alternatives with our relative ranking of their properties for underwater applications. Again, the ranking is not absolute, but is one way of comparing the alternatives in a qualitative way. Gravimetric and volumetric energy density here correspond to the energy produced with an equivalent amount of hydrogen. As for hydrogen, buoyancy and change in buoyancy during the mission affect the energy density at neutral buoyancy. Hydrogen peroxide is given a top rating for depth independence. The reason is that hydrogen peroxide is a liquid, and therefore can be stored in flexible plastic bags pressurized by the ambient seawater. This is a lightweight

Table 1 – Ranking of properties for a selection of hydrogen storage media for underwater use. 1 – Excellent, 2 – Good, 3 – Fair, 4 – Poor. Positive buoyancy and no buoyancy change during mission are evaluated as an advantage for reasons explained in the buoyancy section.

	Gravimetric energy density	Volumetric energy density	Buoyancy	Buoyancy change during mission	Energy density at neutral buoyancy	System simplicity	Depth independence
Pressure tank of steel, 200 bar	4	4	3	1	4	1	2
Pressure tank of composite with liner, 700 bar	2	3	1	1	2	2	3
Liquid hydrogen, incl. thermal insulation and pressure hull	1	2	3	1	2	4	3
Reforming of hydrocarbons (e.g. methanol), incl. BOP	2	2	3	3	3	4	2
Reversible metal hydride	4	2	4	1	4	1	2
Metal/water reaction (e.g. Mg powder+ seawater), incl. BOP	2	2	4	3	3	4	2
Chemical hydride (e.g. $NaBH_4$), incl. BOP	2	2	3	1	2	4	1

Table 2 – Ranking of properties for a selection of oxygen storage media for underwater use. 1 – Excellent, 2 – Good, 3 – Fair, 4 – Poor. Positive buoyancy and no buoyancy change during mission are evaluated as an advantage for reasons explained in the buoyancy section.

	Gravimetric energy density	Volumetric energy density	Buoyancy	Buoyancy change during mission	Energy density at neutral buoyancy	System simplicity	Depth independence
Pressure tank of aluminium, 200 bar	4	4	3	2	4	1	2
Pressure tank of composite, 300 bar	3	3	1	2	3	2	3
Liquid oxygen, incl. thermal insulation and pressure hull	1	2	3	2	2	3	3
Hydrogen peroxide (50%)	3	3	3	2	3	3	1
Chlorate candles (e.g. $NaClO_3$)	3	2	4	3	3	4	3

depth-independent storage solution, in contrast to rigid pressure resistant reactant tanks.

The fact that oxygen is stored or generated on board the AUV brings along the option of operating the fuel cell on pure oxygen. This is one of the major design choices to be made in the development phase of the AUV fuel cell system. The fuel cell stack can be fed with pure oxygen, or with an artificial air atmosphere, where the oxygen concentration is maintained by adding oxygen at the same rate as it is consumed by the fuel cell. Both options have advantages and drawbacks: Feeding the stack with pure oxygen increases its efficiency on cell level by increasing the Nernst potential and reducing diffusion losses in the cathode [11]. The stack can be operated with a lower cathode flow rate than for an air-fed stack. An ejector or a cascading set-up can be sufficient to avoid flooding issues [16,40,41]. This lowers the parasitic power losses compared to the blowers needed to supply air-fed stacks. This simplicity also allows for a more compact fuel cell system. Both factors contribute to a high total energy density.

However, all commercially available fuel cell stacks today are designed for operation on air. Stacks for pure oxygen are available as prototypes or must be custom made, which is a drawback for availability and cost. A high partial pressure of oxygen in the cathode increases membrane degradation, so thicker and reinforced membranes are needed to reduce this effect [40,42–45]. Pure oxygen also represents a higher fire hazard. The start-up and shut-down phases need special attention to avoid rapid degradation [46], especially with no nitrogen present in the cathode. One possible shut-down strategy is to apply an auxiliary load to consume the remaining oxygen in the cathode [47]. In a stack with pure oxygen, this can cause up to 1 bar pressure difference across the membrane, which requires thicker and reinforced membranes.

Buoyancy and trim: AUVs should be designed to have near neutral buoyancy; otherwise they will be unstable and less manoeuvrable in the water at low speed. For easy integration into an existing AUV the fuel cell system should therefore also have neutral buoyancy. However, AUVs normally use payloads with high mass density and therefore contain compensating buoyancy elements (e.g. syntactic foam) to achieve neutral buoyancy. A fuel cell system with positive buoyancy is therefore also advantageous, since it can replace some of the volume occupied by buoyancy elements. This is reflected in the ratings in Tables 1 and 2 and illustrates an important point: The energy density of various fuel cell systems should be compared on total system level and on a basis of neutral buoyancy. A compact reactant storage medium is not necessarily an advantage if you need to include large volumes of buoyancy elements to compensate for its negative buoyancy.

Changes in buoyancy during operation must be compensated for. In a fuel cell system where both reactants and reaction products are stored in non-flexible containers, buoyancy will not change during the mission. In such a system buoyancy is easily managed, but the storage volume for reaction products will reduce the energy density. On the other hand, if the reactants are stored in flexible plastic bags, such as for hydrogen peroxide, and all the product water is stored, the buoyancy will decrease as hydrogen peroxide is consumed. The reason is that the volume of the plastic bag decreases and gives room for an equal extra volume of seawater inside the AUV. This extra volume of seawater increases the total weight of the AUV, reducing the buoyancy. To compensate for this, an equal mass of product water must be pumped out of the water tank of the AUV. This is called active ballasting, and requires a water pump with a size and power consumption that will increase with depth, thus reducing the energy density of the system. These considerations are reflected in the ratings in Tables 1 and 2, where hydrogen and oxygen storage systems are ranked by the relative magnitude of buoyancy change. Note that the tables do not state if the buoyancy change is positive or negative. In some cases, the buoyancy change of the hydrogen and oxygen storage media cancel each other out, so it is important to evaluate the combined buoyancy change. Thus, a comparison of energy density only makes sense for the complete energy system on a neutral buoyancy basis *throughout the AUV mission.*

The trim of the AUV is determined by the distribution of weight and buoyancy. The trim of the fuel cell system should be constant as reactants are consumed, otherwise the AUV can become unstable in the water at low speed. This is why, in a fuel cell system using pure hydrogen and oxygen as reactants, the centre of gravity for the full reactant tanks should be the same as for the full product water tank. If consumption of reactants shifts the point of gravity for the fuel cell system, this must be counteracted by including equipment for active trimming, e.g. by pumping water between an aft and a forward container. This equipment inevitably reduces energy density.

Ambient conditions: The fuel cell system must tolerate the ambient conditions, including corrosive seawater, ambient pressure and organic growth. Sensitive equipment, such as the fuel cell stack and electronics, must be placed in a pressure tight, sealed container. This represents a large weight penalty, especially for AUVs with high depth ratings. The container also introduces new challenges related to operation of fuel cells in a closed environment.

Operation of fuel cells in a sealed container: In a sealed container, fuel cell operation has several challenges. One is condensation: Product water and humidity from the fuel cell must be collected; otherwise the humidity in the tank atmosphere will become too high and give condensation. Condensation can cause electronics or other sensitive equipment to malfunction or corrode inside the tank. A second challenge is cooling of the fuel cell stack: Ambient seawater is an unlimited heat sink, but heat transfer from stack to seawater can be cumbersome with air cooling. Liquid cooling could be a better alternative, but requires heat exchangers that withstand the pressure of ambient seawater. Heat loss from the fuel cell to the container atmosphere may also require a cooling device inside the container. A third challenge is accumulation of inert gases: Any traces of non-consumable gases in the supplied reactants will build up in the container or in the reactant loops and increase the internal pressure over time. As long as the pressure increase is small, this does not represent a problem. But for long-endurance missions the purity of reactants must be very high to avoid unmanageable pressure increase. A fourth challenge is accumulation of hydrogen or oxygen in the container: Most fuel cells require that a small amount of hydrogen is purged out of the anode loop at periodic intervals. If the fuel cell is fed by pure oxygen with a similar circulation loop as for hydrogen, the same need for purging is present on the cathode side. The purged hydrogen cannot be released directly to the container atmosphere, since it will increase the internal container pressure and also cause an explosive atmosphere. So it must be removed by some means, for instance by catalytic combustion. This issue is troublesome during the start-up and shutdown phase of the fuel cell, where various purging strategies should be employed to prevent stack degradation [46]. Achieving this without releasing too much reactants to the container atmosphere is difficult.

Chosen solutions in FFI's underwater fuel cell system

The previous section listed the challenges related to operation of fuel cells under water. In this section we present the design of FFI's underwater fuel cell system and explain how the various challenges have been overcome in this system.

An overview of FFI's fuel cell system was given in a previous paper [34]. Fig. 1 shows a simplified process diagram with the main components, and Fig. 2 shows a picture of the system outside the sealed container.

The fuel cell system is built around a Ballard FCvelocity®-9SSL V4 PEM fuel cell stack. An off-the-shelf hydrogen/air stack was chosen due to commercial availability and low cost. The stack is placed in a sealed container that protects it from ambient seawater. The dimensions of the container are chosen so that it fits into a commercial AUV. The container is filled with air, and the stack is supplied with air from the container using a GAST rotary vane air pump. During fuel cell operation, the oxygen concentration in the container is maintained by supplying pure oxygen from the oxygen generator. Hydrogen is supplied from tanks outside the sealed container. The system is designed for a nominal power of 1 kW.

The following paragraphs go into more detail on how we have solved the listed challenges:

Hydrogen storage/generation: 200 bar steel tanks were used as hydrogen storage containers as a preliminary solution. Steel tanks are heavy and not a feasible hydrogen storage solution for AUVs. So hydrogen storage is one of the remaining challenges to be solved for our system. As discussed above, a strong candidate is composite tanks. Such tanks are already the preferred hydrogen storage medium in fuel cell cars [48,49], but have so far not been qualified for underwater use. An attractive property of the tanks is positive buoyancy. To obtain neutral buoyancy, most AUVs contain a substantial volume of syntactic foam. This volume can be replaced by composite hydrogen storage tanks, providing both hydrogen and the necessary buoyancy. This advantage is reflected in Table 1. However, commercially available composite tanks are not designed for high external pressure and seawater, so further development is needed to benefit from this technology in AUVs.

Oxygen storage/generation: FFI's solution is based on our experience with hydrogen peroxide from the Al/H_2O_2 semi fuel cell [31]. The depth independence of hydrogen peroxide storage is an attractive property (Table 2). In our fuel cell system, oxygen is generated from hydrogen peroxide according to the following reaction:

$$H_2O_{2(l)} \rightarrow H_2O_{(l)} + \tfrac{1}{2}O_{2\,(g)}\ \Delta H = -98.3\ \text{kJ}$$

Fig. 3 shows an overview of FFI's oxygen generator. It was developed in-house specifically for the fuel cell system. It operates on technical grade 50% hydrogen peroxide which is pumped into the reactor of the oxygen generator. The pump is regulated to maintain 400 kPa absolute pressure in the reactor. If the AUV operates at more than 30 m depth, the pump could be replaced by a valve, since the plastic bag with hydrogen peroxide would be pressurized by the ambient seawater.

Hydrogen peroxide decomposes to oxygen and water in a reactor filled with a silver mesh catalyst (Fig. 4). Technical grade hydrogen peroxide is stabilized, which causes a very low reaction rate and catalyst deactivation. Therefore it must be destabilized before use. For safety reasons, the destabilization process takes place in the hydrogen peroxide supply line right before it enters the reactor. The reactor is thermally

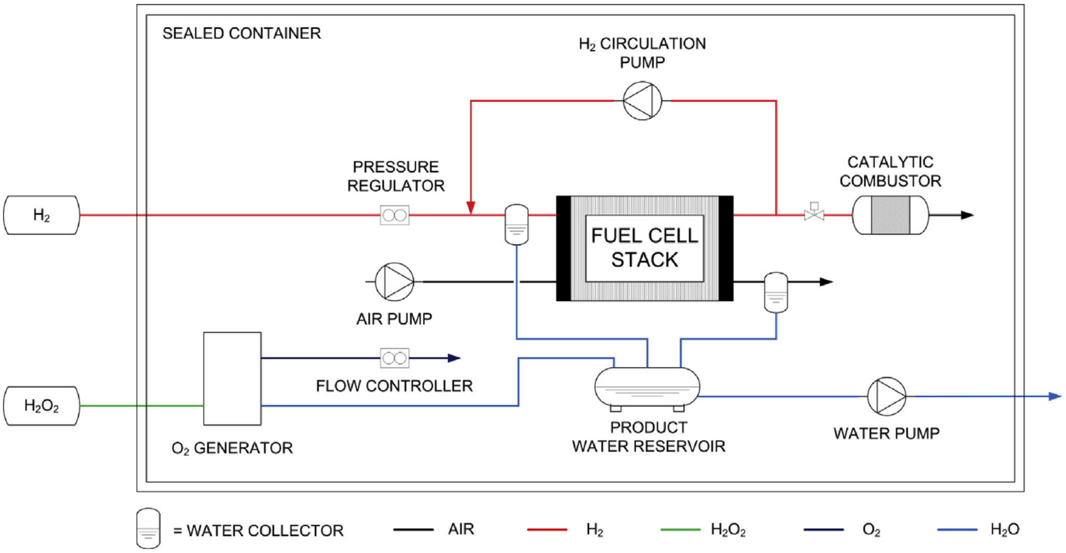

Fig. 1 – Simplified process diagram of FFI's fuel cell system. Electric equipment, instrumentation and heat exchangers have been excluded for clarity.

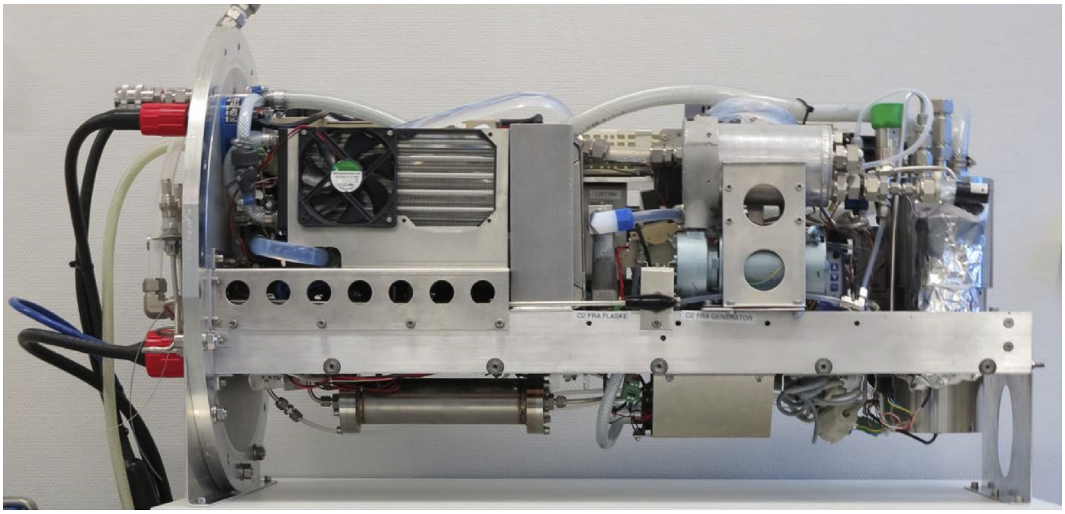

Fig. 2 – FFI's fuel cell system outside the sealed container. Photo: FFI.

insulated and heats itself up due to the exothermic reaction. Under steady state operation, the reactor temperature reaches 136 °C.

The reaction product leaving the reactor consists of a mixture of oxygen, water vapour and liquid water. The mixture enters the reservoir tank (Fig. 5) where it is cooled so that most of the gaseous water is condensed. The reservoir tank serves both as an oxygen gas reservoir and a collector for condensed water. Surplus water is transferred periodically to the product water reservoir.

The oxygen passes through a set of filters before it enters the container atmosphere through a flow controller. The first filter is a steel pipe with silica gel that absorbs humidity and impurities from the technical grade hydrogen peroxide. The second filter is a steel pipe with HiSiv™ 3000 zeolite that absorbs remaining hydrogen peroxide impurities. The third filter is a 5 μm particle filter. An initial assessment showed that the silica gel and zeolite filters were gradually deactivated by the humid oxygen, so they must be dimensioned according to the planned operating time. For the 24 h demonstration 386 g silica gel and 112 g zeolite were used in the first and second filter, respectively. We did not assess regeneration of filter media in our work. The filter set can be further optimized to reduce its size and weight.

In our system, the oxygen generator is placed inside the sealed container. Another option would be to design it for operation in direct contact with ambient seawater, thus allowing it to be positioned outside the sealed container. This would require extra insulation of the reactor, but may still give a more compact system due to reduced container size.

Buoyancy and trim: Using hydrogen peroxide as oxygen source means that the AUV will become heavier during the

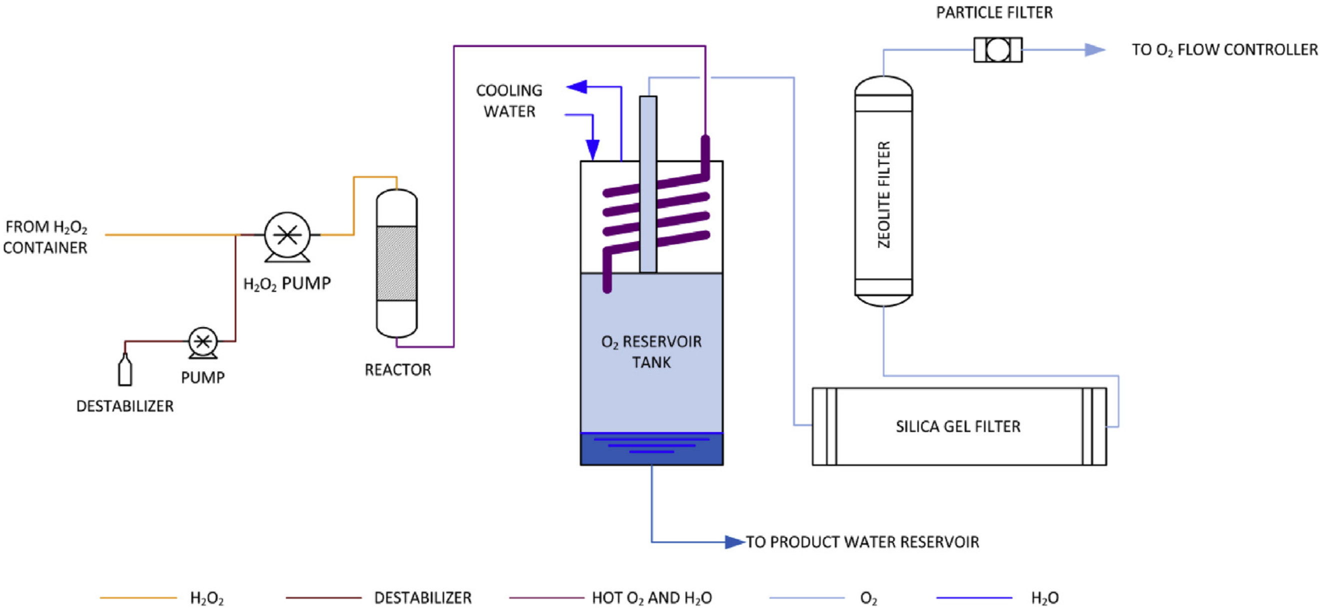

Fig. 3 – Simplified process diagram of the oxygen generator.

mission if all the product water is stored on board. To compensate for this, an equivalent amount of water must be pumped out of the product water reservoir. The pump used so far in FFI's system can only expel water to a few meters' depth and must be replaced with a more powerful pump in the future development of the system. For missions where noise is an issue, the noise generated by pumps with interface to ambient sea water must be evaluated.

In order to compensate for a redistribution of mass as reactants are consumed, the product water can be stored in two tanks, one in each end of the AUV. The tanks should be spherical to minimize tank weight at high depth ratings. The water can be pumped from one tank to the other to maintain constant trim. This solution has not yet been implemented in our system.

Ambient conditions: All sensitive equipment is placed inside a sealed cylindrical container. The fuel cell stack with BOP components are protected from the ambient seawater. The hydrogen tank and the plastic bags with hydrogen peroxide should be placed outside the sealed container to keep its size as small as possible.

Operation of fuel cells in a sealed container: Condensation in the sealed container is avoided by removing humidity and liquid water from the air leaving the fuel cell stack. A process diagram of the air flow circuit in the fuel cell system is shown in Fig. 6. The outlet air first enters an in-house designed water collector, removing liquid water from the flow. The liquid water captured in the water collectors is transferred to a product water reservoir (Fig. 1). After the water collector, the outlet air passes through a Humidicore™ enthalpy wheel which transfers humidity and heat from the outlet air to the

Fig. 4 – Top internal view of the reactor (left) with top end cap (right). The reactor is filled with a silver mesh catalyst. Both top and bottom end caps contain a perforated plate. Photo: FFI.

Fig. 5 – Exploded view of reactor (top) and oxygen reservoir tank (bottom) with integrated cooling tank. Illustration: FFI.

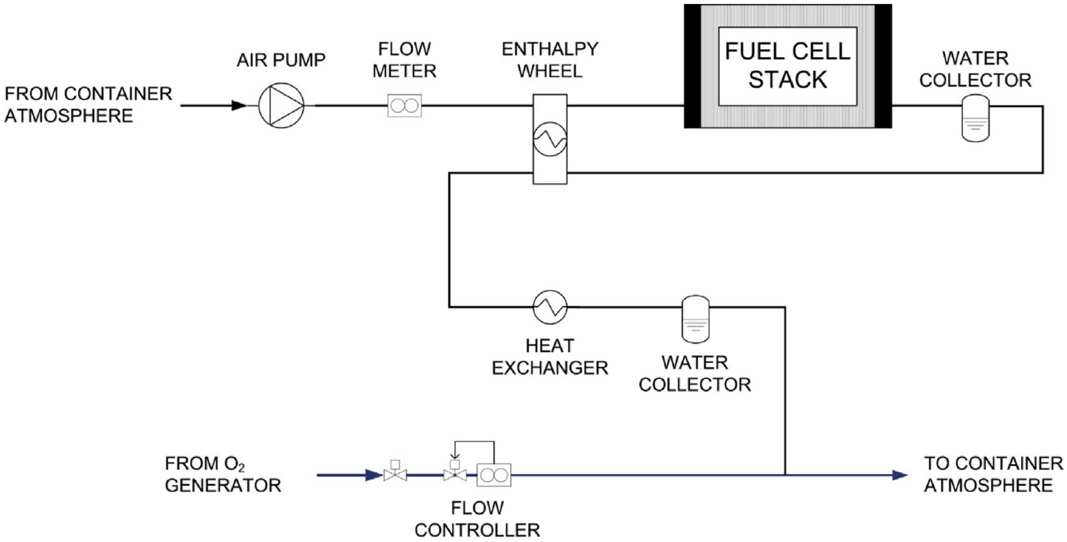

Fig. 6 – **Simplified process diagram of the air flow circuit in the fuel cell system.**

inlet air. Next, the air is further cooled by ambient seawater in a counter flow heat exchanger before it passes a second water collector, mixes with supplied oxygen from the oxygen generator and is released to the sealed container. The heat exchanger is dimensioned so that the exiting air is cooled to near seawater temperatures. The container atmosphere is controlled to a temperature higher than the ambient seawater, ensuring non-condensing conditions. Control of the container atmosphere temperature is achieved by balancing the heat transfer from the fuel cell stack with cooling in a heat exchanger that circulates the container atmosphere.

Cooling of the fuel cell stack is achieved by liquid cooling. The Ballard FCvelocity®-9SSL V4 fuel cell stack is equipped with internal cooling channels, and a cooling loop with distilled and ion exchanged water transports the fuel cell heat to a heat exchanger that is cooled by ambient seawater. The same seawater cooling loop is also used by the oxygen generator and the outlet air coolers.

Build-up of inert gases is controlled by using 99.999% pure hydrogen and by filtering the produced oxygen. A slight pressure increase in the sealed container during long missions is inevitable, but manageable, since the cathode and anode pressures can be increased accordingly.

Build-up of hydrogen in the container is avoided with an in-house designed catalytic combustor. Fig. 7 illustrates the principle. Purged hydrogen enters a cylindrical housing with a platinum coated ceramic monolith. A metal plate near the inlet distributes the hydrogen over the monolith cross-section area. Hydrogen reacts with oxygen inside the monolith, producing water. Moist air exits the combustor. The outlet of the combustor is connected to the air inlet of the fuel cell air pump, so that humidity can be collected in the air flow loop of the fuel cell stack. Initial tests revealed that a separate air supply was necessary to maintain the reaction rate in the monolith. Therefore, a small air fan was installed at the inlet of the combustor, supplying fresh air to the monolith between the hydrogen purges.

Hydrogen slip through the combustor must be avoided. If too much hydrogen is purged at once, some hydrogen will pass the monolith without reacting, thus increasing the hydrogen concentration in the container. By limiting the purge duration and purge valve orifice, hydrogen slip is avoided. In the start-up phase, a similar approach was applied. The anode channels cannot be flushed with hydrogen as recommended by the supplier, but are gradually filled with eight consecutive 2 s purges. This is within the hydrogen processing capacity of the combustor.

System demonstration

The functionality of the fuel cell system was demonstrated during a 24 h test under water in June 2014. The demonstration was carried out in a water basin simulating the thermal interface to seawater (Fig. 8). Results from the demonstration have been reported earlier [34]. Stack current and voltage throughout the test are reproduced in Fig. 9. The demonstration verified the functionality of all subsystems and that the developed fuel cell system can operate in a stable and reliable manner in a sealed container under water. With this demonstration, the system reached a technology readiness level (TRL) of 6 [50].

Further work

The 24 h demonstration marked the end point of the development phase at FFI. Bringing the technology to the next readiness level requires involvement by a commercial AUV supplier. The following improvements are foreseen:

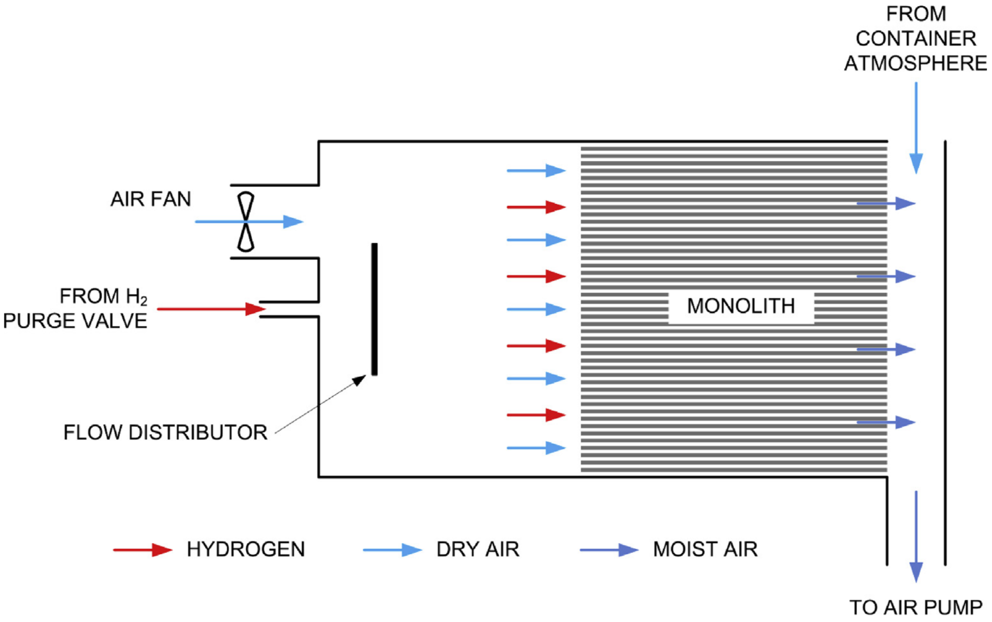

Fig. 7 – Working principle of the hydrogen catalytic combustor.

Fig. 8 – FFI's fuel cell system in operation during the 24 h demonstration. Photo: FFI.

- Further optimization of the fuel cell system to increase power density
- Develop composite hydrogen storage tanks for underwater use
- Include equipment for active ballasting and trim into the system
- Include a DC/DC converter and buffer battery for electrical integration with the AUV

With these improvements established, the system will be ready for integration into an existing AUV and subsequent sea trials. This will bring the system to TRL 7.

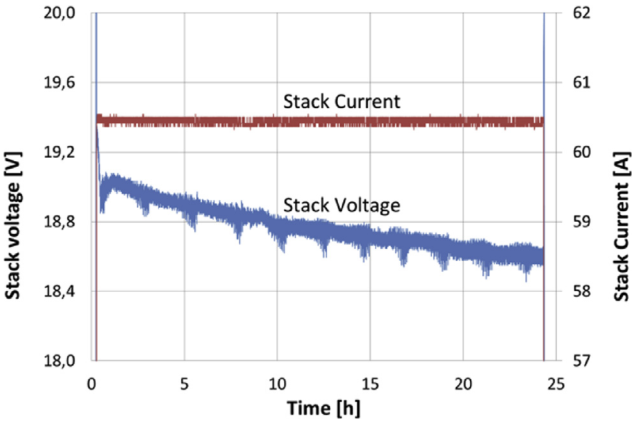

Fig. 9 – Stack voltage and current during the 24 h demonstration. The observed voltage loss was largely recoverable, and the stack voltage was close to the last start value in the next run. Reproduced with permission from Gilljam et al. ECS Transactions. 2016; 71:145–54.

Conclusion

Developing long-endurance AUVs is one possible pathway to reduce the need for an expensive mother ship. Long-endurance AUVs can open up for more challenging mission types than what is possible today. Fuel cell systems can increase the endurance of AUVs beyond what batteries can provide. Several challenges exist for underwater operation of fuel cell systems. These are related to storage or generation of hydrogen and oxygen, buoyancy and trim, and the demanding environment of the ambient seawater. Protecting the fuel cell inside a sealed container brings along more challenges related to condensation, cooling and accumulation of inert gases or reactants. In our development of a fuel cell system for long-endurance AUVs, we have addressed and solved many of these challenges. The reported solutions enabled a 24 h demonstration of FFI's fuel cell system under water.

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