Fuel Cell Technologies for Defence Applications

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Abstract By virtue of their distinct features like autonomy, low signatures, no emissions, high specific energy etc., fuel cells could find a number of applications in the defence sector. Depending on the specific context, the requirement could be for a wearable, portable or distributed power supply. Powering unmanned aerial vehicles, ground vehicles and autonomous underwater vehicles form a separate regime. High levels of efficiency, reliability, reproducibility, robustness to meet the MIL standard environmental tests etc., are the prerequisites for military hardware. The salient features of fuel cells are touched upon in this context and design approach for a fuel cell based AIP system for submarines is discussed in brief.

Keywords Fuel cells · Soldier power · Portable power · Auxiliary power · Unmanned vehicle propulsion · AIP for submarines

1 Introduction

Defence forces look forward to self sufficiency in every situation and location. Power and energy supply must be robust, reliable and versatile. Batteries of several types and specifications have been specially engineered and are in wide use by the Army for their forward area detachments and by the Air force and Navy for autonomous vehicles and remote operation fields. The concept of fuel cell demonstrated by Dr. William Grove in 1839, has undergone numerous innovative up gradations and has got adapted and diversified into several types. Low acoustic signature, low thermal signature, practically no chemical emission, improved specific energy, high energy density, reduced recharging cycle times etc., are important features of fuel cells weighing against the best of battery choices, as far as the military segment is concerned. These features are of significance to the civil sector as well. Still the industry has not been able to penetrate the market, to the

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extent it should have; despite the global green energy campaign. According to a 2015 review, cumulative installed capacity of fuel cells since 1995 is just about 1 GW [1] and the shipment of units forecast for 2015 is around 160,000, all categories included.

Batteries and Fuel cells are both power on demand devices based on electrochemical energy conversion. In batteries the stored chemical energy is released as electrical energy as a result of reactions between the electrodes and the electrolyte. Once the reactants are consumed, the battery stops delivering power and needs to be recharged using electrical energy from external sources. In fuel cells, though electrical energy is generated through electrode reactions, the reactants per say are not stored in the cells and can continue to give rated power output as long as supply of the fuel and oxidant could be maintained.

Polymer electrolyte fuel cell (PEFC) uses a solid polymer electrolyte membrane for exchange of the H^+ ion facilitating the anode and cathode reactions of Hydrogen and Oxygen, using Platinum and alloy catalysts. Relatively lower service life, stringency of material specifications and the need for extremely high purity of Hydrogen, etc., are the limiting factors. Solid oxide fuel cells (SOFC) are made up of ceramic and cermet electrodes and electrolyte systems such as Yttria Stabilized Zirconia (YSZ). They are robust in nature. No gel or liquid or polymer membrane is involved. However, the engineering challenges are several, since the operating temperatures are as high as 800–1000 °C. Handling Hydrogen gas at such high temperatures is a safety critical issue. In stationary systems SOFC is finding large scale application, primarily due to the flexibility in fuel choice. Ni-cermet anode used in SOFCs, has very poor sulfur tolerance below 800 °C. To be successful in automobiles, PEFC system must operate at 110–120 °C, which causes associated performance and degradation issues [2].

In Phosphoric acid fuel Cell (PAFC), phosphoric acid spread over a porous supporting substrate forms the basic electrolyte layer. Platinum and platinum alloys on Carbon form the catalysts. Handling the corrosive acid, maintaining its concentration and choice of acid resistant materials are the critical engineering challenges. Though the operating temperature is higher in comparison with PEFC, better tolerance to impurities in the reactants is a specific advantage. Overall power to weight ratio is lower than that of PEFC. But PAFC has much longer service life. Alkaline Fuel Cells (AFC) have the fastest kinetics. The electrode support is typically Ni mesh or foam. The separator media is alkali (typically KOH) soaked asbestos membrane. Such systems can use metallic bipolar plates, and thereby reduce cost. However, their vulnerability to poisoning by CO_2, corrosion of the electrodes, dilution of alkali in the cell etc., are issues that restrict the use of AFC. Molten Carbonate Fuel Cells (MCFC) use fused alkali carbonates as primary electrolyte and bipolar plates are of metal alloys. Since operating temperature is high, faster kinetics is possible. Major problem encountered is the corrosion of electrodes.

In all of the above cases hydrogen fuel is supplied externally, either as stored gas/liquid, or through reforming hydrocarbons. Alternately decomposition of peroxides is also practiced as an option. In Direct Fuel Cells (DFC) hydrogen containing materials like methanol or sodium borohydride is directly used as the fuel, rather than using an external fuel processor or reformer, to generate hydrogen online. Such fuel cells are more compact though they suffer from much slower kinetics.

2 Potential Defence Applications

Simplicity, durability, ruggedness and high level of autonomy, are essential features of any military hardware. Systems should have fault diagnostics and self protection features. Detailed maintenance plans, mean time between failures (MTBF), mean time to repair (MTTR), etc. are important statistical parameters of interest to the military customer.

Air force bases in forward areas and remote locations need assured electric power for battery charging, auxiliary power for surveillance and regular power for communication equipment. Long endurance unmanned aerial vehicles also need agile power sources. Navy's strategic need of electrical power is for running the unmanned underwater vehicles and air independent propulsion systems for non nuclear submarines. The land forces cannot be confined to pre chartered fields and terrains. Power supply would have either been destroyed or had never existed in the new posts they occupy. Based on the typical operating environment and user perspectives, army's power requirements can be classified into soldier power, auxiliary power units (APU), autonomous systems, distributed power plants etc. [3]. US department of defence has carried out a comprehensive study and has identified the distinct areas, as soldier wearable and portable power, auxiliary power units for ground vehicles, ships, and aircrafts, non-tactical light-duty vehicles, propulsion power for ships, submarines, autonomous underwater vehicles (AUVs) and unmanned aerial vehicles (UAVs) [4].

2.1 Soldier Power

Portable high density power source is vital for the modern war fighter to meet his C4I system needs. Apart from the communication equipment, power is required for helmet mounted displays, mobile computer, data modems etc. Primary challenge is to keep the system weight low. High temperature PEFC with methanol reformer is a choice for 25–55 W systems. Portable model JENNY 600 S from M/s. SFC Energy can directly power electrical devices or recharge secondary batteries. The fuel cartridge contains methanol and has a capacity of 400 Wh each. Ultracell has been able to pass several models of their reformed methanol fuel cells (RMFC) through the rigorous test procedures of the US army. PEFC based prototypes developed by M/s Ballard power systems is using sodium borohydride as the primary fuel. Naval Materials Research Laboratory, (NMRL), India has developed a 100 W system based on PEFC technology, integrated with online hydrogen generator, for man portable field power applications. The system can provide 100 W power for 10 h for every 1 l of liquid fuel.

Operation at low ambient temperatures of the order of −20 °C, as well as performance at low ambient oxygen levels, typical of the high altitudes has to be specially factored in the design of fuel cells for such applications. For use in desert regions, the system should take care of high temperature autocatalysis of hydrogen donor materials employed. Similarly, if liquid fuels like methanol is used, due consideration should be given to the fuel's flash point. Air breathing systems should employ dust filters engineered to take care of the desert storms. Practically no repair is possible in the field. Systems should have long enough MTBF. Power conditioning to meet the input requirement of specific devices and qualification of system to MIL standards of EMI/EMC are other engineering challenges.

Lower end of soldier power, say around 20 W, can be met by direct ethylene glycol—anion exchange membrane based fuel cell. Ethylene glycol being an anti-freeze material is suitable for low temperature locations like northern sectors of India. Direct Methanol Fuel cells are also showing high potential for such low power applications. A wearable fuel cell together with disposable fuel cartridge can provide higher energy density than the best of the lithium primary cells.

2.2 *Auxiliary Power Units (APU)*

Field deployed vehicles and battle tanks of army need on-board power for electrical and electronic devices in use. Auxiliary power required during 'silent watch' should leave absolutely low signatures. Such systems should be capable of autonomous operation without operator intervention. The system should be engineered to give high levels of reliability under extreme environments of temperature, dust, humidity, shock and vibrations. Processes should not leave observable emissions of chemicals, smoke, light or sound. Ideally their thermal signatures should also be very low. Power conditioners and associated electrical circuitry should conform to MIL standard EMI/EMC specifications. This is a specific application where the conventional diesel power generators can be replaced with fuel cell generators for significant strategic advantages. Weight and volume considerations are important; but not as critical as in the case of man portable systems. However, the systems need to be all weather resistant, robust and highly reliable. Operator intervention and maintenance requirements should be minimal.

NMRL has developed a PAFC based 10 kW generator car that uses an integrated methanol reformer for in situ hydrogen generation. This power source can be used with advantage for ad hoc repair facilities for field equipment. They are also handy for enhancing relief operations in distress management and for providing emergency medical assistance camps in the remote locations.

2.3 Distributed Power Generation

At forward area base camps of the armed forces grid power may not be available. Captive generation is the only alternative. Major portion of base power needs, as well as heating and cooling needs, can be met by fuel cell systems. Combined heat and power (CHP) systems with fuel cells can be very effective at remote locations. Ground handling vehicles can be directly operated by fuel cells, or alternatively fuel cells can charge the battery operated vehicles and equipment. Higher overall efficiency of the system will justify the high initial cost since transportation of fuel to such locations through difficult terrains is very cumbersome and expensive. Maintenance free operation for long periods is a primary requirement. PAFC is a good choice from the life expectancy considerations. But SOFC is more versatile when choice of fuel is considered. For this segment, NMRL has developed a 30 kW truck mounted modular PAFC power plant with integrated methanol reformer.

2.4 Autonomous Systems

Advent of robotics and unmanned vehicles have revolutionised strategies and tactics in the battle field. Unmanned aerial vehicles of diverse capabilities, unmanned ground vehicles used for mine clearing, unmanned NBC reconnaissance vehicles, autonomous underwater vehicles in diverse roles etc., are the new generation technologies aimed at reducing human causalities in situations of conflict. These special platforms require widely varying power sources, typically 10 W for micro aerial vehicles at the low end and up to 3000 W for unmanned ground vehicles.

Unmanned underwater vehicles (UUVs) require power sources with long endurance having high specific energy and power density, beyond what can be met using conventional battery power. In order to realize the full potential, current research focus is on advanced batteries and mini fuel cell systems. Fuel cells can have energy density several folds higher, compared to silver-zinc or lead acid batteries. As the energy storage volume of a UUV increases, fuel cells become more appropriate for enhancement in run duration, compared to even Li-Ion batteries. Unlike batteries which take a long time to recharge, the fuel cell’s tanks can be refuelled quickly, resulting in rapid turnaround times between missions. A wide spectrum of technologies starting from mini-tubular SOFC to light weight PEFCs, conformal DBFCs etc., have been specially developed with success.

Use of hydrogen as compressed gas and oxygen as liquid oxygen(LOX) has been the choice for fuel cell system on ‘URASHIMA’ UUV [5]. Fuel cell is housed in a pressure vessel. Oxygen gas is supplied from a high pressure oxygen gas tank and hydrogen is supplied from the metal hydride contained in a pressure vessel.

Chemical storage and onboard release of oxygen on demand from decomposition of peroxides and perchlorates offers high volumetric efficiency, though weight penalty will be higher [6]. Generation of hydrogen from hydrolysis of borohydrides, is also an available choice. For UUVs the volume constraint is important and it is necessary to minimise the balance of plant. Ease of recharging and refilling, is also one of the important criteria.

Depending on specific missions, UUVs have to dive to very deep ocean (say a few thousand meters) to retrieve data from sea bed sensor systems, or travel at medium depths (say a few hundred meters) for tracking and trailing adversary submarines. In either case the energy density as well as specific energy of the power plant has to be very high. The system should be heat integrated to the full extent, so that net heat thrown out should not increase the ambient temperature inside the electronics compartments. Being deep water vessels hull penetrations are generally avoided. All reaction products are to be contained inside the body. General arrangement of fuel cell and balance of plant should be so designed as to ensure that the progressive shift in centre of gravity and centre of buoyancy, during the run of the UUV are within the permitted hydrodynamic design limits of the platform. The system needs to be engineered to be fully operational even during the extremes of manoeuvres of the vessel. There are UUVs that are designed to run in different modes totalling to several says in a single mission. The command and control during the mission will be by the onboard computer. Power plant reliability has to be absolute, for such applications, where the plant needs to respond to the dynamic load characteristics and function without attention, for several days at a stretch.

Alejandro Mendez et al. [7] has reviewed some of the field demonstrations of autonomous vehicles powered by Fuel cells. Several models of fuel cells developed for AUVs, comparison of fuel options, oxygen storage possibilities and the associated issues are discussed in detail.

2.5 Fuel Cells on Battle Ships

The United States as well as United Kingdom have programmes running, to study the advantages of using fuel cells for powering surface ships. Specific advantages are better efficiency compared to gas turbines and diesel engines, reduced smoke, reduced sound and thermal signatures, lower vibration levels, design flexibility due to modularity etc. Power rating required will be of the order of a few megawatts. Types of fuel cells having potential utility are SOFC, MCFC, PAFC as well as PEFC. On board fuel processing will be inevitable. Use of logistic fuel is very much desired, if dual modes are proposed. Hybridization of direct fuel cells with turbine cycles using the fuel cell by-product heat, as proposed by M/s Fuel Cell energy® [8] can give very high overall efficiencies.

2.6 *Air Independent Propulsion System (AIP)*

Air Independent Propulsion system, popularly known as AIP system, for conventional diesel electric submarines, is a mission critical application for fuel cells. Diesel electric submarines use storage batteries as power source during their subsurface sailing missions. The batteries are recharged using electricity produced by running the diesel generators, for which the boat needs to snorkel. AIP systems cater for charging of the batteries while the submarine is still in the dived condition. The added feature has a force multiplier effect on the role and performance of the submarine, since the vessel can undertake very long underwater sailing missions. Typically the endurance can be up to 2 weeks, whereas a non-AIP submarine has to surface once in almost every 2 days. Of the different types of AIPs, fuel cell based AIPs are considered superior, thanks to its silent operation and low heat generation. Reliability, availability and maintainability of the system are most important for submarine applications. Modular architecture has advantages over a composite system [9]. Even if one of the modules fails, an intelligent control system can regroup and realign the healthy units to give at least a reduced output, thereby enhancing survivability.

AIP module is commonly engineered as an auxiliary standalone unit. The module has to be comprehensive and complete including provision for the fuel processing/storage, oxygen storage and dosing, control and instrumentation systems, microclimate management, safety features, as well as platform interfaces. The fuel cell per say and the balance of plant, together should geometrically conform to the form, fit and design standards of the submarine. The system should satisfy all the platform doctrines.

Structurally the submarine is designed as an externally loaded pressure hull and will be circular in cross section. The add-on AIP section should have only marginal impact on the speed and manoeuvrability of the vessel. As a rule about 10 % extra length is permitted. A typical AIP section can therefore be a cylindrical plug, about 6.5 m in diameter and about 7 m in length. The plug has to be neutrally buoyant and can therefore it can have a typical weight of the order of 200–250 tons.

2.6.1 Weight and Volume Constraints

The volume budget should consider space for passing pipelines cables and trunking through the AIP module to connect between the fore and aft sections as well as passage for crew movement. Apart from refuelling and local maintenance requirements, provision has to be made for shipping in and shipping out of equipment for shop floor repairs and refit. Submarine safety codes stipulate the porosity, i.e., the total volume of equipment in the module, expressed as a fraction of the total volume of the plug. This is a cardinal requirement for the crew safety. With the total reactants loaded, the module should be neutrally buoyant. In case the design calls for any of the by-products of onboard chemical processes to be discharged into the sea, compensating tanks for maintaining the buoyancy criteria has to be provided. The lay out design shall ensure that only minimal shifts in centre of gravity will be experienced, as the reactants get consumed.

2.6.2 Constraints in Equipment Sizing and Lay Out

Loss in energy at any stage will have cascading effects. Primarily, for the same mission endurance more amount of fuel has to be carried, increasing the all up weight. Secondly the lost energy will manifest as heat generated within the compartments leading to increased air conditioning load, which in turn adds to the parasitic load on the system. Efficiency of power conditioners should be at least 95 %. The load dependent voltage characteristics, typical of fuel cells, throw immense challenges to the power system hardware designer.

In general practice the fuel cells are stacked using stress bolts. The level of pre-stress is chosen by the designer with due considerations for the gasket seating force required for the individual cells, the contact pressure required for current collectors of the cells, thermal expansion and stress relaxation characteristics of the prestressed assembly, etc. The stacks have to be configured and engineered to form towers of optimal capacity. The preferred shape of cocooned towers is cylindrical so that the unit can be shipped out through the circular hatch openings. Being equipment onboard the submarine, all equipment designs will have to qualify the shock and vibration standards through use of appropriate shock mounts and anti vibration devices.

2.6.3 Platform Safety Concerns

Any leakage of Hydrogen inside a submarine compartment is strictly prohibited. Measures such as jacketed pipe design and special welding and joining procedures have to be adopted. Reliable leak detection and abatement systems have to be provided for. The designs should be qualified through physical tests of conformity under environmental and cyclic thermal aging processes. Hydrogen requirement for a sortie is to the tune of a few tons. In certain designs of AIP hydrogen is stored in metal hydrides and is desorbed on a temperature swing. To avert the potential hazard from accidental temperature rise and consequent high rate release of hydrogen, the hydride cylinders are located outside the pressure hull. The design calls for hull penetrations to take the gas inside. Optionally hydrogen is produced on board through chemical routes-either by hydride decomposition reactions or by partial oxidation of alcohols or through reforming of diesel. Prima facie this arrangement is safer since there is no bulk storage of hydrogen at any time. However, designing a complex chemical plant for the dynamic conditions of a submarine and engineering the plant for hydrogen safety regimes under continuous operational cycles is a challenge in itself. Behaviour of plant hardware and equipment has to be studied using ship motion simulators. Geometrically the equipment designs have to be tailored to suit the form and fit of cylindrical profile. Process intensification and reliability engineering has to be thorough. Gravity flow conditions under different list, trim and roll conditions of the submarine in motion have to be simulated while qualifying the plant architecture.

Oxygen requirement for a full sortie will be to the tune of 30–40 tons. The most efficient way to store oxygen is as liquid oxygen (LOX). LOX tanks have to be located inside the pressure hull for single hull submarines. Upper limits on thermal leakages are very critical since excessive boiling of LOX can lead to forced venting routines. Designer should ensure that the LOX system does not add to criticalities during the permitted motion cycles of the ship under various environments of shock, vibration and acceleration/deceleration.

3 Concluding Remarks

Fuel cells have come a long way in technology maturity. Still large scale exploitation in both, domestic and industrial segments has not taken place, at the expected pace. Other forms of energy conversion are still remaining competitive. Extensive R&D focused on cost reduction and life cycle cost management is progressing. Defence sector stands to gain significantly from the unique features of fuel cells. The challenges in design and engineering to meet the stringent military standards in reliability, environmental qualification, life cycle management, etc., are to be addressed through a comprehensive and holistic approach. Application development programmes should look at the totality of system and not the fuel cell alone in isolation. In this paper, certain key issues and important engineering challenges to be addressed in development of a fuel cell based AIP system for submarines, has been dealt in some detail in order to illustrate the system engineering complexity.

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