

A Portable Fuel Cell Apparatus and System

Field of Invention

[001] Conventional battery technologies and commercial battery products have low gravimetric energy density values and do not meet the power requirements for soldier applications. The present application relates to an improved portable electrochemical power generation device that is comprised of a fuel cell system and a hydrogen generation system with high gravimetric energy density values for powering the gears, electronics, etc. carried by a soldier. In particular, the application relates to a micro (also called as portable) proton exchange membrane fuel cell (PEMFC) based power system that can utilize the hydrogen gas generated from a solid hydride material (where the hydrolysis reaction follows the exothermic MgH_2 hydrolysis reaction pathway). This entire power system is also called as soldier power pack and it significantly reduces the weight/volume of the powering device for an individual soldier due to its high energy density feature compared to the same energy storage capacity battery module.

Background

[002] Currently, all of the essential power needed for a soldier is usually obtained by using Li-ion, Li-polymer, or some other battery technology that is being qualified for military use. Since the batteries have to carry the active material for anode and cathode electrodes regardless of their chemistry, a soldier's stay in the field can be extended in theory by carrying more batteries, though the final weight of the battery module becomes extremely heavy for multiple-day missions. Energy storage capacity of batteries are usually identified based on their specific energy density values and this parameter can be measured either as the energy storage capacity in a unit weight (Watt.Hour/kilogram) or unit volume (Watt.Hour/Liter) basis. As a rule of thumb, the higher the gravimetric energy density or volumetric energy density of the selected battery technology, the longer the soldier can stay in the field without recharging or replacing the depleted battery cells. In order to further clarify it, current state-of-the-art lithium batteries for soldier portable power applications have a gravimetric energy density of 120 to 180 Wh/kg values. Military related portable power requirement for an individual soldier would usually fall into 0 to 20 Watts range. Assuming that the soldier's gear is consuming 16 Watts of electrical energy constantly, then for a 1-day mission (or 24 hours of operation at 16 Watts), there

will be a need of an energy storage capacity of 384 Wh and this would be equivalent of 3.2 kg of battery if the battery has a gravimetric energy density of 120 Wh/kg value. Current battlefield and austere environments are already requiring an individual soldier to carry a large amount of gear in order to successfully complete his/her mission in the field. Furthermore, current battlefield conditions are not only requiring to stay in the field for the individual soldiers for much longer times (multiple days) without coming to the base for provisions, but also new generation electronics gears are also utilizing more and more power due to their advanced features. Batteries are not meeting the power requirement of individual soldiers and there is a critical need for lightweight and high energy density power technologies that will facilitate the mission completion for the individual soldiers in the field.

[003] A micro fuel cell is an excellent portable power source of electricity because of its high energy density compared to conventional batteries. Fuel cell based powering devices are becoming an essential hardware for soldiers in the austere environments due to their advantages in reducing the weight of the power device for a soldier. These fuel cells may be direct methanol fuel cell (DMFC), alkaline fuel cells, solid oxide fuel cell (SOFC) or proton exchange membrane fuel cell (PEMFC). The power levels of micro fuel cells are usually limited to a power envelope of 0 to 20 Watts for portable applications. The same power output limitations are also applicable to soldier power when an individual soldier is carrying a powering device that is portable and utilizing micro fuel cells (i.e., 0 to 20 Watts). Among these different fuel cell technologies, PEMFC is the most promising fuel cell technology because of its excellent electrochemical performance within the temperature envelope of -20 to 80 °C and high-power density for the fuel cell stack component (up to 5.5 W/cm²). With the use of ultralight-weight fuel cell stacks, such as HES' Aerostak products (<https://www.hes.sg/aerostak>), gravimetric energy density values of up to 700 Wh/kg can easily be achieved at the overall system level depending on the form of the hydrogen (meaning how the hydrogen is stored). In short, PEMFC based powering devices' gravimetric energy density values are 4 to 6 times higher than the batteries' gravimetric energy density values, which is ideal for soldier power applications.

[004] PEMFCs utilizes hydrogen gas at the anode side and oxygen (from the ambient air) at the cathode side electrochemically and produces power. Though, a major limitation for the use of PEMFCs has been the need for high-density hydrogen storage. Hydrogen can be

initially generated as gas or liquid and then stored inside a properly designed cylinder at an off-site location or the hydrogen can be generated in the field in real time by using a solid hydrogen storing material such as hydrides. Currently available high-pressure cylinders are bulky in volume, heavy, and can store limited quantities of hydrogen gas due to their low working pressure. Most of the portable cylinders have volumetric capacity of several liters, weighs several kilograms, and have a working pressure of up to 700 bars. Despite the fact that liquid hydrogen storage option has a much higher energy storage capacity compared to gaseous high-pressure hydrogen storage option, large volume and mass for the storage vessel and boil-off issues prevented its use for soldier power applications. On the other hand, on-demand and real-time generation of hydrogen from solid materials such as hydride compounds have a large potential from an engineering feasibility for soldier power applications due to easy extraction of the hydrogen approaches from the hydride material itself.

[005] There exist a number of hydride materials that can be used for hydrogen gas generation such as sodium borohydride, ammonia borane, alanates, magnesium hydride, etc. Hydrolysis and thermolysis are the most common methods of extracting hydrogen from such hydride materials. Hydrolysis approach refers to the chemical reaction of hydride material with water (whether this is pure water, caustic water, or acidic water) with or without a catalysts bed. Thermolysis method refers to extraction of hydrogen from the hydride material with heat without using any other ingredients. Hydrogen gas generated with the thermolysis route usually requires the thermal decomposition of a known quantity of the hydride material (most of the time in the pelletized form) instantly and hence there is a need for a high-pressure vessel to contain the generated hydrogen gas in a small chamber or small volume. The weight of the high-pressure vessel usually is very high in order to provide a reasonable safety margin for its safe operation and hence not suitable for soldier power applications. In short, hydrolysis method has been identified as a more promising approach for hydrogen generation from hydride materials due to its engineering feasibility and lightweight nature of the final hardware for soldier power applications.

[006] Kim and Lee, published an article “A complete power source of micro PEM cell with NaBH₄ microreactor”, in Micro Electro Mechanical Systems, 2011 IEEE 24th International Conference. This micro PEM cell includes a micro reactor for hydrogen

generation from NaBH₄ alkaline solution. The main disadvantage of this technology has been the use of highly caustic and hazardous chemicals such as sodium hydroxide or potassium hydroxide in order to stabilize the lifetime of the sodium borohydride material. Furthermore, the by-product of the sodium borohydride hydrolysis reaction is highly viscous and needs to be flashed out of the catalyst bed by using water, which creates additional logistics requirements for the individual soldiers. There is a need for a better hydride material that does not require use of hazardous chemicals or create additional logistics issues.

[007] While ammonia borane has a higher hydrogen storage percentage compared to sodium borohydride, during the hydrolysis of the ammonia borane, ammonia gas is also generated, and the hydrogen stream needs to be cleaned from this ammonia gas contaminant (since this is a poisoning chemical for PEMFCs) before the generated hydrogen enters the fuel cell stack. This gas cleanup adds more complexity to the portable power device, increases its weight and volume, and hence makes it difficult to use for soldier power applications.

[008] A hydride material that is based on magnesium such as MgH₂ can also be used for the hydrogen gas generation via the hydrolysis route. Hydrolysis reaction of MgH₂ can either be classified as exothermic or endothermic. Depending on the amount of water used, the hydrolysis reaction mechanism changes drastically for the magnesium hydride powder (see Eqs. 1 and 2). Furthermore, the state of the water (liquid or steam) also affects the outcome of the hydrolysis reaction. Some of the most important hydrolysis reactions of MgH₂ with water (regardless of the state of the water) can be given as:



Hydrolysis reaction of MgH₂ with steam is highly exothermic when the molar ratio of MgH₂ to water is kept at 1, meaning MgH₂'s number of moles is equal to steam's number of moles (see Eq. 1, hereinafter it is called exothermic MgH₂ hydrolysis reaction). As the number of moles is increased for the water (see Eq. 2), the heat production becomes less (in layman's term, it is becoming more endothermic). Despite the fact that the Eq. 2 is theoretically considered to be exothermic in nature, but the amount of heat generated is not sufficient to sustain the hydrolysis of MgH₂ when too much water is consumed, and it

requires the use of an external power source to input an additional amount of heat in order to complete the hydrolysis reaction. To sum up, as it can be seen in Eq. 1 and Eq. 2, the amount of water used for the hydrolysis reaction drastically affects the quantity of the heat produced. Once the hydrolysis reaction is initiated with an initial heating, it will be advantageous to utilize this exothermic heat to its fullest in order to sustain the hydrolysis reaction without adding any additional external heat from an external power source such as a battery. For this reason, exothermic hydrolysis reaction pathway that is provided in Eq. 1 is the preferred pathway for this application to generate a significant amount of exothermic heat and then use this exothermic heat to sustain the hydrolysis reaction after the initial pre-heating step without any additional heat from an external power source.

[009] Due to the constantly changing battlefield and mission capability requirements, an individual soldier has to carry a significant number of power-hungry gears and electronic devices to successfully complete the mission at hand and this requires the use of ultra-lightweight fuel cell system and an advanced hydrogen generation system that has high specific energy density compared to batteries. Hence, there is a critical need for soldier power packs that are better than conventional batteries in order to increase a soldier's mission capability in the field.

Summary

[0010] The following information and descriptions provide an understanding of the present invention.

[0011] The present application is comprised of an improved portable micro fuel cell system and portable hydrogen generator system that are specifically tailored to power the electronics, gears, etc. carried by an individual soldier by generating hydrogen on-demand and in-real time from magnesium hydride via exothermic MgH_2 hydrolysis route that is given in Eq. 1 and then consume the generated hydrogen inside a PEMFC stack to produce the desired amount of electrical energy.

[0012] The portable micro fuel cell system is comprised of a single lightweight micro fuel cell stack, balance of plant components, and a single fuel cell controller. Micro fuel cells are usually classified as powering devices for a power output of 0 to 20 Watts and very ideal for portable applications. In general, an individual soldier's power requirement will

be in the range of 0 to 20 Watts and hence the fuel cell stack used in the stated portable fuel cell system is capable of producing 0 to 20 Watts of electrical energy in order to keep the weight of the overall system at the nominal or minimum value to reduce the burden on the soldier. The nominal operation of fuel cells requires their usage at electrical efficiencies greater than 50% in order to obtain a hardware that is better batteries. Despite the fact the stated micro fuel cell can produce power in the envelope of 0 to 20 Watts, the nominal operational envelope for the micro fuel cells usually fall into 10 to 20 Watts in order to have an electrical efficiency that is greater than 50%. Furthermore, operating outside of this envelope drastically shortens the lifetime of the fuel cell component, which may increase the cost of the ownership for the portable micro fuel cell apparatus and system. Hence, in this application, the nominal operational power output of the stated micro fuel cell is limited to 10 to 20 Watts in order to achieve the desired lifetime, which is 500 hours of operational hours for open cathode/ closed anode design based fuel cell technology. The balance of plant components is comprised of the following items: fuel cell casing, fuel cell stack manifold, fan, pressure regulator, pressure sensor, temperature sensor, supply valve, purge valves, gas stream cleaning filters, LCD display, hydrogen gas transfer plumbing, unused hydrogen and water purging plumbing, fuel cell stack conditioning electronics, and etc. The stated balance of plant components can be used as single or plural items in order to facilitate the safe operation of the fuel cell system to reliably produce an electrical energy of 0 to 20 Watts by consuming the hydrogen gas coming from the hydrogen generation system. The stated portable fuel cell system can be assembled as a single unit (meaning as a stand-alone unit) for ease of integration to a stand-alone hydrogen generation unit or it can be intimately assembled with the hydrogen generation unit in a more compact and ruggedized form factor.

[0013] The portable hydrogen generation system is comprised of a water tank module assembly and hydride reactor in order to generate sufficient quantity of hydrogen for the portable micro fuel cell system stated in this application. The main functionality of the water tank module is to contain all of the balance of plant components for the operation of the hydride reactor inside the assembly in order to pre-heat the hydride reactor vessel (including the magnesium hydride powder), move the precise quantities of water from the water tank to the hydride reactor for hydrogen generation reaction, and provide orientation-independent operation capability for the entire system (meaning moving the liquid water from the water tank to hydride reactor under any orientation). The water tank

module assembly can be comprised of the following components: water tank, water pump, orientation-independent water movement mechanism, pressure sensor, temperature sensor, valves (with different functionalities), filters, buffer or condenser unit, a small battery, essential plumbing to move the water into the hydride reactor and collect the hydrogen from the hydride reactor, and etc. The hydride reactor has the main functionalities of containing the magnesium hydride fuel and all of the essential other reactor components needed to allow the water vapor or steam entering into the hydride reactor, allowing the hydrolysis reaction be carried very efficiently while utilizing the exothermic heat generated (from the hydrolysis reaction) in order to sustain the hydrolysis reaction without inputting an extra amount of electrical energy from the small battery module or from any other external power source, collect the generated hydrogen and remove the contaminants from the hydrogen stream, cooling down the hydrogen gas temperature to a level that is appropriate to the safe operation of the stated fuel cell system's fuel cell stack, and transfer the this clean and cooled down hydrogen to the fuel cell stack via the essential plumbing. The hydride reactor vessel is comprised of: reactor housing and reactor cap to contain the hydride fuel and provide a hermetical seal, electrically resistive porous tube to carry and distribute water vapor or steam into the hydride powder, porous tube(s) or a porous substrate to collect and transfer the generated hydrogen gas from the hydride reactor to the condenser and cooling coil to that is located on the outside of the hydride reactor. Since the stated micro fuel cell in this application is for an individual soldier, the stated portable fuel cell apparatus is capable of generating 0 to 20 Watts to power the soldier-worn electronics, gears, etc. Despite the fact the stated micro fuel cell can produce power in the envelope of 0 to 20 Watts, the nominal operational envelope for the micro fuel cells usually fall into 10 to 20 Watts in order to have an electrical efficiency that is greater than 50%. Operating outside of this envelope drastically limits the lifetime of the fuel cell component, which may increase the cost of the ownership for the portable micro fuel cell apparatus and system. Hence, in this application, the nominal operational power output of the stated micro fuel cell is limited to 10 to 20 Watts in order to achieve the desired lifetime, which is 500 hours of operational hours for open cathode/ closed anode design based fuel cell technology. Considering that a soldier might be staying in the field up to 24 hours, it is preferred that a hydride cartridge should be designed to store enough magnesium hydride powder inside the cartridge for up to 24 hours of constant operation within variable power level of 0.1 Watt to 20 Watts and then replace the depleted cartridge with another single unused or new hydride cartridge. In this application, it is envisioned

that the soldier would take a single unused cartridge and replace the single depleted magnesium hydride cartridge in the stated portable micro fuel cell apparatus. This would require a hydrogen storage capacity of 2.4 Wh to 480 Wh, preferably 250 Wh to 350 Wh, more preferably 280 to 325 Wh, even more preferably around 300 Wh. Based on this power consumption and hydrogen storage requirements, it is estimated that the water tank would for the hydride reactor needs to be sized to contain around 0.96 to 192 mL of water, preferably 100 mL to 140 mL, more preferably 110 to 130 mL for the soldier power. Furthermore, the hydride reactor is designed to contain 1.2 to 240 grams of magnesium hydride material, more preferably 120 grams to 180 grams of the hydride material, more preferably 140 to 160 grams of the hydride material, even more preferably around 150 grams. The magnesium hydride storage capacity of the hydride vessel is limited to the nominal operational power envelope of the micro fuel cell component. The stated portable hydrogen generation system can be assembled as a single unit (meaning as a stand-alone unit) for ease of integration to the portable fuel cell system or it can be intimately assembled with the portable fuel cell system in a more compact and ruggedized form factor.

Brief Description of the Drawings

[0014] Figure 1A describes the major constituents (in the form of the system schematic) of the portable proton exchange membrane fuel cell (PEMFC) apparatus (where the entire system is also called as soldier power pack) and its overall fluidic/electrical/communication interfacing of the present application;

[0015] Figure 1B illustrates the assembled form of the portable proton exchange membrane fuel cell (PEMFC) apparatus (i.e., soldier power pack) and its overall architecture where the fuel cell system and hydrogen generation system are intimately integrated into a single form factor;

[0016] Figure 2 shows the fuel cell manifold assembly that is comprised of the major balance of plant components needed to safely operate the fuel cell system located in the above-mentioned PEMFC apparatus;

[0017] Figure 3 illustrates the major constituents of the water storage vessel (also called as water tank manifold) that is comprised of the major balance of plant components needed to

safely operate the hydrogen generation system located in the above-mentioned PEMFC apparatus;

[0018] Figure 4 illustrates a reactor vessel and its components constituted in the above-mentioned PEMFC apparatus;

[0019] Figure 5 illustrates the alternative embodiment of the assembled form of the portable proton exchange membrane fuel cell (PEMFC) apparatus (i.e., soldier power pack) that is given in Figure 1B;

[0020] Figure 6 shows an alternative embodiment of the fuel cell manifold assembly that is given in Figure 2;

[0021] Figure 7A shows the fuel cell system and the water storage vessel in the assembled form as an alternative embodiment given in Figure 2 and Figure 3;

[0022] Figure 7B shows an alternative embodiment of the fuel cell manifold assembly that is given in Figure 2 which is needed to safely operate the fuel cell system located in the PEMFC apparatus described in this invention;

[0023] Figure 8 illustrates an alternative embodiment of the water storage vessel (also called as water tank manifold) that is given in Figure 3 which is needed to safely operate the hydrogen generation system located in the PEMFC apparatus described in this invention;

[0024] Figure 9 illustrates an alternative embodiment of the reactor vessel that is given in Figure 4;

[0025] Figure 10 illustrates a simplified schematic layout of the soldier power pack for the portable PEMFC apparatus and system that is described in this invention;

[0026] Figure 11 shows the portable fuel cell apparatus and system (also called as soldier power pack) that was built by HES Energy Systems and placed inside a military-grade pouch and fully closed (left image) and the pouch cover open (right image);

[0027] Figure 12 shows the portable fuel cell apparatus and system that is given in Figure 11 with the portable fuel cell apparatus and system placed inside an inner pouch (left image) and the actual portable fuel cell power apparatus and system taken outside of the inner and outer pouch completely (right image);

Reference Numbers

2	Proton exchange membrane fuel cell (PEMFC) stack
3	Hydrogen generator
4	Pressure regulator
5	Hydrogen outlet
6	Cable
10	Reaction chamber
11	Quick-disconnect coupling (for water supply)
13	Quick-disconnect coupling (for H ₂ outlet)
14	Water outlet port
15	Pump
16	Water storage vessel
20	Hydrogen line
21	Pressure sensor
22	Pressure relief valve
25	Battery
26	External load or electric load
30	Hydride powder
36	Heater
37	Temperature sensor
100	Portable hydrogen proton exchange membrane fuel cell (PEMFC) apparatus and system
101	Housing
102	Hydrogen reactor vessel
103	Vessel cap
104	Heat insulator
105	Replaceable hydride cartridge or dry hydride cartridge
106	Mounting plate
109	Manifold
110	Controller
120	Cooling coil
122	Buffer tank
123	Port
124	Outlet
126	Recollection valve
128	Supply valve
130	Purifying filter
132	Pressure sensor
134	Exhaust port
136	Purge valve
140	Porous PTFE membrane
142	Weighted clunk

144	Tubing
145	Discharge line
146	Check valve
162	Switch
163	Heater port
164	Signal
165	Output port
170	USB port
200	Portable hydrogen proton exchange membrane fuel cell (PEMFC) apparatus
201	Fuel cell system
202	LCD display
203	Fluidic and electrical interface between the hydride fuel cartridge and the water tank module
204	Water tank module
205	Hydride fuel cartridge
206	LCD display and its controller
207	Fuel cell stack fan
208	Supply valve
209	Purge valve
210	Supply and purge valve set
211	Fuel cell stack manifold
300	H ₂ inlet from the hydride reactor
301	H ₂ to condenser
302	H ₂ through condenser
303	H ₂ through cooling coil
304	H ₂ flow into fuel cell stack manifold
305	H ₂ O and unused H ₂ purge out from the fuel cell stack manifold
306	H ₂ inlet from the condenser
307	Fuel cell stack inlet port
308	Fuel cell stack outlet port
400	Water tank
401	Disc filter
500	Reactor H ₂ O inlet
501	Reactor H ₂ O outlet
502	Reactor electrical connector
503	Reactor manifold
S1	Solenoid
S2	Solenoid
S3	Solenoid

Detailed Description of Embodiments

[0028] One or more specific and alternative embodiments of the present application will now be described with reference to the attached drawings. It shall be apparent to one skilled in the art, however, that this invention may be practiced without such specific details. Some of the details may not be described at length so as not to obscure the invention. For ease of reference, common reference numerals or series of numerals will be

used throughout the figures when referring to the same or similar features common to the figures.

[0029] FIG. 1A shows a schematic of a portable hydrogen proton exchange membrane fuel cell (PEMFC) system 100 according to an embodiment of the present application. The entire PEMFC system 100 is enclosed in a housing 101, which is preferably made from a polymer, lightweight metal, combination of polymer and lightweight metal, or any other relevant material that can be used for the specified portable fuel cell apparatus and system. The PEMFC system 100 is portable and is designed to be carried by a user, more specifically a soldier to carry his/her mission at hand. The following describes such portable PEMFC system 100, which provides a safe, useful and portable power system to the soldier. As seen from FIG. 1A, the PEMFC system 100 includes at least a proton-exchange membrane fuel cell (PEMFC) stack 2 (whether this may be a single cell or multiples of single cells that forms an array that is called a stack) and a single hydrogen generator 3 (that is magnesium hydride based); the single hydride based hydrogen generator 3 includes a hydrogen reactor vessel 102, an accompanying vessel cap 103 and a water storage vessel 16. The vessel cap 103 closes the hydrogen reactor vessel 102 to provide a leak-proof reaction chamber 10; in one embodiment, the vessel cap 103 is connected to the reactor vessel 102 by welding. In use, a hydride powder 30 is disposed inside the reaction chamber 10, which is hydrolysed with steam via following the exothermic MgH_2 hydrolysis reaction pathway in order to produce hydrogen gas. The hydrogen reactor vessel 102 is a double-walled vessel, with the space between the walls being evacuated to a vacuum. The exterior surfaces of the hydrogen reactor vessel 102 and vessel cap 103 are covered by a heat insulator 104, with part of the heat insulator 104 being shown in FIG. 1A. With double-walled vacuum insulation around the reactor vessel 102, a thickness required of the heat insulator 104 is significantly reduced; the reduced bulk of the heat insulator 104 means reduction in the external dimensions of the heat insulator and hence reduction in weight for the overall PEMFC system 100. To allow quick replacement of the hydrogen reactor vessel 102 and vessel cap 103 assembly, a water supply tubing, hydrogen outlet, heater, etc. that enter the reactor vessel 102 are supported on a mounting plate 106. In addition, the water supply tubing may be connected at the mounting plate 106 via a quick-disconnect coupling 11; similarly, the hydrogen outlet may be connected at the mounting plate 106 via another quick-disconnect coupling 13. Hydrogen gas produced in the reactor vessel 102 is finally supplied to the PEMFC

stack 2 through a pressure regulator 4 and a hydrogen outlet 5. A gas outlet from the fuel cell stack 2 is connected to an exhaust port 134 located on a manifold 109; the exhaust port 134 is fluidly connected to a purge valve 136, which is operable to vent out gas from the PEMFC stack 2; in use, the purge valve 136 is controlled by a signal from a controller 110 via a solenoid S3 on the purge valve 136. The purge valve 136 and all the fluid flow components that will be described for connecting into the manifold 109 are of a cartridge type; this is to achieve a more compact configuration for a portable PEMFC system 100.

[0030] Again referring to FIG. 1A, water is stored in the water storage vessel 16. Water is supplied into the reaction chamber 10 via a water outlet port 14 located on the water storage vessel 16, a pump 15, a tubing 144 connecting a discharge port from the pump 15 to a check valve 146 and another tubing joined to the coupling 11 before terminating inside the reaction chamber 10. Preferably, the check valve 146 is located inside the manifold 109. In one embodiment, the tubing 144 is selected to provide a predetermined rupture pressure range, so that during an emergency state of operation, for eg. inside the reaction chamber 10 or caused by an exterior environment outside of the PEMFC system 100, the tubing 144 is operable to rupture and stop the supply of water into the reaction chamber 10; when this happens, the check valve 146 ensures that the reaction chamber 10 remains closed. The tubing 144 and the check valve 146 provide a non-recoverable fail-safe mechanism for this portable PEMFC system 100.

[0031] Hydrogen produced in the reaction chamber 10 via exothermic MgH_2 hydrolysis pathway is supplied through a hydrogen outlet port or quick-disconnect coupling 13 located on the mounting plate 106 and flows into a hydrogen line 20; preferably, the hydrogen line 20 is located inside the manifold 109; inside the manifold 109, the hydrogen line 20 is connected to a pressure sensor 21 and a pressure relief valve 22. The hydrogen line 20 then goes into a cooling coil 120, which is disposed inside the water storage vessel 16, with an outlet of the cooling coil leading to a buffer tank 122. The hydrogen gas passes through the cooling coil 120 and is being cooled from a high temperature range of 100 to 600 °C, preferably of 200 to 400 °C, more preferably of 300 to 400 °C (in the reaction chamber 10) to about 5-100 °C, preferably to 10 to 50 °C, more preferably to 20 to 40 °C; any water that condenses out from the hydrogen gas is collected inside the buffer tank 122; the condensed water is recycled into the water storage vessel 16 via a recollection valve 126, which is operable by a signal from the controller 110 to a solenoid S1. Hydrogen

flowing through an outlet 124 at the buffer tank 122 is connected to a purifying filter 130 before the pressure is controlled by the pressure regulator 4. The hydrogen supply upstream of the purifying filter 130 is controlled by a supply valve 128 and an accompanying solenoid S2. The supply valve 128 may be used to stop the hydrogen gas supply when the fuel cell 2 is being purged or when the fuel cell stack is being conditioned if it is based on an open cathode technology that needs frequent hydration cycles, for eg. at the end of a power generation cycle or at an end of a start-stop cycle, as determined by the controller 110 and/or soldier. The controller 110 is electrically connected to the PEMFC stack 2 by a cable 6.

[0032] The water storage vessel 16 is spill-proof. As seen from FIG. 1A, the water storage vessel 16 is a fully enclosed vessel of about 9.6 to 192 mL of water, preferably 100 mL to 140 mL, more preferably 110 to 130 mL capacity but has a removeable membrane 140 made from a porous PTFE; the porous PTFE membrane 140 allows gas to pass through but is impermeable to water; any hydrogen gas that is recycled back through the water recollection line, ie via port 123, may escape through the porous PTFE membrane 140; in this manner, pressure in the water storage vessel 16 is maintained at atmospheric pressure. The water storage vessel 16 being spill-proof and maintained at atmospheric pressure is a second safety feature built into the PEMFC system 100. In addition, a weighted clunk 142 is disposed at a free end of a water intake tube that leads to a suction port of the pump 15. The weighted clunk 142 ensures that the free end of the water intake tube is completely submerged under water irrespective of orientation of the entire PEMFC housing 101.

[0033] In this application, the hydride powder is a magnesium hydride (MgH_2). To hydrolyze MgH_2 , the reaction chamber 10 is preferably pre-heated to about 40-120 °C, preferably to 60-110°C, more preferably to 80-100 °C in order to favor the exothermic MgH_2 hydrolysis reaction pathway; initial heating of the reaction chamber 10 is carried out by the controller 110 providing a signal to close a switch 162 connected to a heater port 163, which is electrically connected to the heater 36. Initial power for the heater 36 is obtained from a battery 25; once sufficient hydrogen is generated from the reaction chamber 10 and operation of the PEMFC system 100 is sustainable, electric power generated from the PEMFC system 100 is fed through the cable 6 to the controller 110. Hydrolysis of the MgH_2 is controlled by controlling the amount of water fed through the pump 15 according to a demand of an electric load 26 connected to an output port 165; in

one embodiment, when the voltage V in the cable 6 exceeds that of the battery 25, electric power from the PEMFC system 100 charges up the battery 25. Since this application utilizes the exothermic MgH_2 hydrolysis pathway to generate hydrogen from the MgH_2 powder 30 that is disposed inside the hydrogen reactor vessel 102, a temperature sensor 37, such as a thermocouple, is used to monitor the temperature inside the reaction chamber 10. Signal from the temperature sensor 37 is fed to the controller 110, together with signals from the hydrogen pressure sensors 21, 132. As seen from FIG. 1A, the pressure sensor 21 is located near the reaction chamber 10 while the pressure sensor 132 is located at the PEMFC stack 2 that is encased inside the portable hydrogen PEMFC system 100. Also seen from FIG. 1A, a user may provide a start-stop signal to the controller 110. It is possible that the cable 6 includes one or more signals from the controller 110 to control operation of the fuel cell stack 2; for eg, a signal to the fuel cell stack 2 may control a ventilation fan disposed in the fuel cell stack 2 to ensure a constant supply of O_2 /air, to control the temperature of the fuel cell stack, and to dissipate excess H_2 that may accumulate inside of the housing 101 via overboard leaking or during purging events.

[0034] FIG. 1B shows a portable hydrogen proton exchange membrane fuel cell (PEMFC) apparatus 200 incorporating the above PEMFC system 100. The PEMFC apparatus 200 is thus high-energy dense, portable and lightweight; it is used to extend mission endurance for a soldier. The PEMFC apparatus is rated at 0 to 20 Watts, preferably 8 to 18 Watts, more preferably 10-16 Watts of power consumption on average to power the electronics, gears, etc. carried by an individual soldier. The PEMFC apparatus 200 uses dry hydride powder 30 disposed in the hydrogen reactor vessel 102 (which constitutes a replaceable hydride cartridge 105) to generate hydrogen on demand via exothermic MgH_2 hydrolysis reaction pathway, and the controller 110 controls the electric output port 165 (via a signal 164) for powering up and/or charging an external load 26, such as a portable device, electronics, gears that are carried by the soldier. In addition, the controller 110 controls the electric supply power from the battery 25 to the heater 36.

[0035] The dry hydride cartridge 105 is rated at 2.4 Wh to 480 Wh, preferably 250 Wh to 350 Wh, more preferably 280 to 325 Wh, even more preferably around 300 Wh, and the battery 25 is selected for a power capacity to allow the depleted dry hydride cartridge 105 to be hot-swapped to facilitate easy replacement of the dry hydride cartridge 105 without power interruption at the external load 26 which is connected to the output port 165. As

compared to batteries, carrying more hot-swappable hydride cartridges would drastically improve and increase the energy-to-weight ratio due to its higher energy density, and consequently extend mission endurance for soldiers. The above PEMFC system 100 includes 3 modules: (1) a fuel cell stack 2 and its balance of plant components; (2) a water storage vessel 16 and its balance of plant components; and (3) a reactor vessel 102 with its balance of plant components. The respective modules can be assembled as separate modules in separate housings or intimately integrated and assembled inside a housing 101 which provides a physical case and protection for the various components to allow the PEMFC system 100 to function as a portable power system.

[0036] As seen from FIG. 2, the PEMFC system 100 assembly includes the following:

- i. the PEMFC stack 2; is the primary power source for the PEMFC system 100 that produces electric energy through the electrochemical reaction of oxygen at the cathode side of the fuel cell stack and hydrogen at the anode, where hydrogen is oxidized to protons at the anode electrocatalysts layer, protons are transferred to the cathode through the membrane and electrons sent to cathode via the external electrical connection, and at cathode proton ions react with oxygen molecule and electrons in order to create electric energy and water as the by-product;
- ii. the battery 25; serves as a secondary power source for the PEMFC system 100 to supplement power during the start-up process before the PEMFC stack 2 supplies electric power; the battery 25 is also used for heating up the reaction chamber 10 to initiate chemical reaction in the reactor vessel 102;
- iii. the electric output port 165; this allows recharging of any portable battery cells and/or powering of portable electric apparatus carried by the soldier;
- iv. the manifold 109; is to provide flow pathway before hydrogen gas enters the fuel cell 2.

The manifold 109 includes at least:

- a. three miniature solenoid valves 126, 128, 136;
- b. the purifying filter 130; the hydrogen purifying filter maintains purity of the hydrogen content; and
- c. two pressure sensors 21, 132;
- v. the pressure regulator 4;
- vi. the controller 110; and
- vii. a USB port 170 for debugging and maintenance (including electronic data extraction).

An LCD display may be connected through a serial port (not shown in the figures)

at the controller 110 to indicate to the user the amount of energy capacity left in the hydrogen reactor vessel 102.

[0037] FIG. 3 shows the water storage vessel. The water storage vessel 16 includes the following components:

- i. the water storage vessel 16; it has a capacity of about 0.96 to 192 mL of water, preferably 100 mL to 140 mL, more preferably 110 to 130 mL and contains water to hydrolyse the magnesium hydride powder 30 to produce H₂ gas on demand via the exothermic MgH₂ hydrolysis reaction pathway;
- ii. the cooling coil 120; serves to cool H₂ gas with the aid of water contained in the water storage vessel 16; temperature of the hydrogen gas is cooled from a high temperature range of 100 to 600 °C, preferably of 200 to 400 °C, more preferably of 300 to 400 °C (in the reaction chamber 10) to about 5-100 °C, preferably to 10 to 50 °C, more preferably to 20 to 40 °C before hydrogen gas enters the PEMFC stack 2;
- iii. the water pump 15; to supply controlled amounts of water to the reaction chamber 10 to allow hydrolysis of the magnesium hydride powder 30 to produce H₂ gas;
- iv. the buffer tank 122; condenses and separates water vapor entrained in the hydrogen gas during hydrolysis of the magnesium hydride powder 30;
- v. the recollection valve 126; recollects water from the buffer tank 122 and recycles water to the water storage vessel 16; and
- vi. the weighted clunk 142; allows entry of water from the water storage vessel 16 to the water pump 15 irrespective of orientations of the water storage vessel 16 by making use of gravity force.

[0038] FIG. 4 shows the hydrogen reactor vessel 102. The hydrogen reactor vessel 102 contains a dry magnesium hydride powder 30 disposed inside the double-walled vacuum insulated hydrogen reactor vessel 102 that offers excellent heat insulation. This allows the contents in the hydrogen reactor vessel 102 to retain their heat for an extended period of time, while an exterior of the reactor vessel remains cool and safe to touch. The reaction between water and magnesium hydride produces hydrogen gas which is then supplied to the PEMFC stack 2 to generate useful (electric) energy to the user. The hydrogen reactor vessel 102 contains of the following sub-components:

- i. the heater 36; powered by the battery 25 to supply sufficient heat to initiate hydrolysis of the hydride powder 30;
- ii. the water delivery tube; delivers controlled amounts of water from the water storage vessel 16 through the water pump 15 to the hydride powder 30;
- iii. the H₂ gas outlet port; H₂ gas produced during hydrolysis of the hydride powder 30 is directed out of the reaction chamber 10 to the PEMFC stack 2; and
- iv. the temperature sensor 37, such as thermocouple; to monitor the reaction temperature within the reaction chamber 10.

[0039] Now, operation of the hydrogen generator 3 system is described: Upon switching on, water from the water storage vessel 16 is supplied in controlled amounts into the hydride cartridge 105 through the water pump 15. The heater 36 is powered up by the battery 25 to heat up the reaction chamber 10 and heat up the liquid water and convert this into a high temperature steam to initiate the exothermic MgH₂ hydrolysis reaction between the magnesium hydride powder 30 and water vapor to produce H₂ gas. When the reaction becomes optimized or stabilized, the exothermic nature of the hydrolysis reaction allows for self-sustainment of reaction and no longer requires the aid of the heater 36. The H₂ produced during the reaction is cooled from a high temperature range of 100 to 600 °C, preferably of 200 to 400 °C, more preferably of 300 to 400 °C (in the reaction chamber 10) to about 5-100 °C, preferably to 10 to 50 °C, more preferably to 20 to 40 °C before hydrogen flows through the manifold 109 towards to the PEMFC stack 2. At the PEMFC stack 2, H₂ and O₂ reactants are reacted with each other electrochemically and as a result, electrical energy is produced with high efficiency, which is then channeled to the load 26 (such as charging of an external battery or electric device) for the soldier.

[0040] The start-up sequence for the hydrogen generation system can take almost up to 10 minutes. During substantially the first 10 minutes of the operation, the energy output from the PEMFC system 100 is predominantly contributed by the battery 25 while chemical reaction builds up within the reaction chamber 10. When significant amount of H₂ (flow) is generated from the reaction to produce electric energy, operation of the PEMFC stack 2 takes over to supply electric power to the external load 26 via the electric output port 165. The battery 25 together with any rechargeable battery connected to the output port 165 would in-turn be recharged by the electric energy produced at the PEMFC stack 2.

[0041] The controller 110 includes an algorithm that responds adaptively to the utilization level remaining in the hydride cartridge 105. For eg., if the hydride cartridge 105 is about half utilized, there is likelihood of water being present in the reaction chamber 10; in this case, more heat is required and the controller 110 algorithm responds adaptively to extend the heater heating duration before more water is supplied into the reaction chamber 10.

[0042] Figure 5 illustrates an alternative embodiment of the assembled form of the portable PEMFC apparatus 200 that is given in Figure 1B. In this embodiment, the electrical output port 165, LCD display 202, fuel cell system 201 and its balance of plant components, water tank module 204 and its balance of plant components, the fluidic and electrical interface between the hydride cartridge and water tank module 203 have been arranged in order to obtain a lightweight and compact powering device through intimate integration of the different modules into a single hardware and eliminate the need for replications amongst the components, which has a gravimetric energy density of about 300 Wh/kg value.

[0043] Figure 6 illustrates an alternative embodiment of the fuel cell manifold assembly that is given in Figure 2 with a different layout. Main controller 110 is directly placed underneath the LCD display and its controller 206 and the electric output port 165 is placed in the vicinity of these two components. Furthermore, pressure regulator 4, pressure sensor 132, purifying filter 130, supply and purge valve set 210, and fuel cell stack fan 207 are rearranged on the fuel cell stack manifold 211 (compared to Figure 2 layout) in order to further reduce the physical size of the fuel cell system.

[0044] Figure 7A illustrates the integration of the fuel cell system and water storage vessel in the assembled form as an alternative embodiment given in Figure 2 and Figure and the flow direction of the H₂ gas generated inside the reactor vessel 102. Hydrogen gas generated inside the reactor vessel 102 initially passes through the H₂ inlet of the reactor 300, then it flows into the condenser 301, then moves through the condenser 302, then moves along the cooling coil 303, then this hydrogen flows into the fuel cell stack manifold 304, after it passes through the fuel cell stack, it then exists the fuel cell stack as unconsumed H₂ and H₂O.

[0045] Figure 7B shows an alternative embodiment of the fuel cell manifold that is given in Figure 2 with a different layout of the constituents forming the assembly. In this setup, H₂ inlet from the condenser 306 is connected to the H₂ supply valve 208 and enables the transfer of cooled down H₂ gas to pass through the H₂ inlet from the condenser 306 then to the H₂ supply valve 208, then this same hydrogen is directed into the ion exchange filter 130 in order to remove the contaminants, then hydrogen pressure is sensed with the pressure sensor 132, and then generated hydrogen gas passes through the pressure regulator 4 before it flows through the stack inlet port 307. At this stage, hydrogen gas will flow through the anode side of the fuel cell stack 2 and majority of the fuel species will be consumed in order to generate the desired electrical energy. As the by-product, water will be generated. The unconsumed H₂ gas and the by-product water 305 will then be moved to the exit of the fuel cell stack 2 and purged away from the fuel cell stack outlet port 308.

[0046] Figure 8 describes an alternative embodiment of the water storage vessel (also called as water tank manifold and assembly) that is given in Figure 3 with a different layout for the constituents forming the assembly. This new layout yields a very compact and highly integrated assembly that not only reduces the weight, but also the overall volume of the portable fuel cell apparatus that is disclosed in this application. In this new embodiment, the water tank 400 has an L-shape form and it covers the battery 25, the water pump 15 is directly placed inside the water tank 400. Recollection valve 126, buffer tank or condenser 122 and disc filter 401 are intimately placed close to each other in order to eliminate the dead space among the different components. Pressure sensor 21 that reads the hydrogen gas pressure inside hydride reactor and interface components 203 located between the hydride fuel cartridge 205 and water tank module 204 to manage the operation of the hydride reactor are also rearranged in a way to further reduce the length of gas, fluidic, and electrical plumbing compared to the embodiment provided in Figure 1B. With these improvements, it was possible to reduce the weight of the portable PEMFC apparatus to 1 kg and its volume to less than 1.4 liters.

[0047] Figure 9 describes an alternative embodiment of the reactor vessel that is given in Figure 4. In this embodiment, reactor H₂ inlet 500, reactor H₂ outlet 501, and reactor electrical connector 502 are integrated onto the reactor manifold 503 and cover of the

reactor to further eliminate the need for a separate manifold and reduce the weight compared to the design that is provided in Figure 4.

[0048] Figure 10 shows the simplified layout of the soldier power pack for the portable PEMFC apparatus and system that is given in Figure 1A. In this new concept, it is envisioned that hydride reactor is hot swappable and a depleted hydride reactor can simply be pulled out from the portable PEMFC apparatus by grabbing the housing and pulling out in a vertical direction without any rotation movement. In order to achieve this, the hydride reactor and the water tank module have the mating quick-disconnect couplings that have O-rings for providing the sealing.

[0049] Figure 11 and Figure 12 provides the images of the actual soldier power pack product that was designed and built by HES Energy Systems (in collaboration with STK-AME/Singapore) inside a military-grade pouch.

[0050] While specific embodiments have been described and illustrated, it is understood that many changes, modifications, variations and combinations thereof could be made to the present invention without departing from the scope of the present invention.

Claims

Claim 1. A portable hydrogen proton exchange membrane fuel cell (PEMFC) system comprising a housing enclosing the following:

- a proton exchange membrane fuel cell (PEMFC) stack;
- a water storage vessel;
- a magnesium hydride powder disposed in a hydrogen reactor vessel for the hydrogen reactor vessel;
- a water pump disposed between the water storage vessel and the reactor vessel;

wherein the PEMFC stack, the water storage vessel and the reactor vessel are in fluid communication; and

- a check valve disposed in a discharge line connecting the water pump to the reactor vessel, wherein the discharge line comprises a tubing with a predetermined rupture pressure range;

further comprising a cooling coil disposed in the water storage vessel to cool down hydrogen gas generated from an exothermic MgH_2 hydrolysis reaction of the magnesium hydride powder in the hydrogen reactor vessel;

further comprising a buffer tank and a recollection valve, wherein the buffer tank is in fluid communication with the cooling coil and the recollection valve is operable to recycle water condensed in the buffer tank via cooling of the hydrogen gas into the water storage vessel.

Claim 2. The system according to Claim 1, further comprising a purifying filter disposed in fluid communication with the buffer tank.

Claim 3. The system according to Claim 2, further comprising a supply valve disposed in fluid communication between the buffer tank and the purifying filter, wherein the supply valve is operable by a solenoid.

Claim 4. The system according to any one of Claims 1-3, wherein fluid communication for the hydrogen gas is formed in a manifold.

Claim 5. The system according to Claim 4, wherein the manifold further supports the check valve defined in Claim 1.

Claim 6. The system according to any one of preceding claims, wherein the reactor vessel has a double-wall construction, which interior of the double-wall is evacuated to a vacuum.

Claim 7. The system according to Claim 6, further comprising a vessel cap disposed for closing a mouth of the hydrogen reactor vessel.

Claim 8. The system according to Claim 6, further comprising heat insulation disposed on an exterior of the hydrogen reactor vessel and the vessel cap.

Claim 9. The system according to any one of the preceding claims, further comprising a controller, wherein the controller receives signals from a temperature sensor and a pressure sensor, and in response turns on a battery to supply electric power to a heater disposed in the hydrogen reactor vessel before voltage generated from the system exceeds voltage across the battery.

Claim 10. The system according to Claim 9, further comprising an electric outlet port, wherein the electric outlet port is controlled by the controller so that the hydrogen reactor vessel is hot-swappable when the system is operating and power supply at the electric outlet port is not interrupted.

Claim 11. A method of using a portable hydrogen proton exchange membrane fuel cell (PEMFC) system comprising:

- connecting a water pump to supply water from a water storage vessel to a reactor vessel, wherein a pump discharge line comprises a tubing with a predetermined rupture pressure range and a check valve;

- thermally insulating the reactor vessel with a vacuum double wall and, on an exterior of the hydrogen reactor vessel, surrounding the hydrogen reactor vessel with a thermal insulator;

- hydrolysing a hydride powder disposed in the reactor vessel with a controlled amount of water supplied through the water pump to generate hydrogen gas on demand via exothermic MgH_2 hydrolysis reaction pathway; and

- directing the hydrogen gas to flow from an outlet of the reactor vessel to a PEMFC stack to generate electric power;

further comprising:

passing the hydrogen gas through a cooling coil disposed in the water storage vessel to cool the hydrogen gas to a predetermined temperature;

condensing water vapour in the hydrogen gas in a buffer tank, which buffer tank is disposed downstream of the cooling coil, so that the condensed water collected in the buffer tank is recycled back into the water storage vessel via a recollection solenoid valve;

Claim 12. The method according to Claim 11, further comprising:

purifying the hydrogen gas by passing the hydrogen gas through a purifying filter disposed downstream of the buffer tank.

Claim 13. The method according to any one of Claims 11-12, further regulating operation of the PEMFC with a controller, wherein the controller comprises an algorithm that responds adaptively to a utilization level remaining in the hydride powder.

Claim 14. The method according to Claim 13, wherein the battery allows hot-swapping of the hydrogen reactor vessel when the hydride powder is depleted and the system is still operating.

Claim 15. A portable hydrogen PEMFC apparatus comprising

the portable hydrogen PEMFC system of claim 1;

a hydrogen generation system;

a battery;

a casing;

a pouch;

where the PEMFC system further comprises a PEMFC controller, an LCD display and its controller, fluidic/electrical/communication and diagnosis interfaces, and a balance of plant components of the portable hydrogen PEMFC system;

where the PEMFC stack is based on an open cathode / closed anode fuel cell design and it produces power in the range of 0 to 20 Watts and has a nominal operational envelope of 10-20 Watts,

where the open cathode / closed anode PEMFC stack does not carry an external humidifier device and utilizes an electromechanical connection between the ends of the PEMFC stack in order to humidify the PEMFC

stack and the electromechanical connection is located on the PEMFC controller,

where the PEMFC controller manages the safe operation of the PEMFC system,

where the PEMFC stack manifold is used to integrate all of the PEMFC system components onto a common platform and as a single module form,

where the PEMFC balance of plant components are comprised of a fan, temperature sensor(s), pressure sensor(s), pressure regulator(s), purifying filter(s), supply and purge valve(s), and a PEMFC stack manifold,

where the operation of the hydrogen generator system is controlled based on the internal pressure of the fuel cell stack, hydrogen gas consumption of the fuel cell stack, and/or power output of the fuel cell stack,

where the hydrogen generator system is comprised of a hydride fuel cartridge, a water tank module, a hydrogen generation system controller, fluidic/electrical/communication interface components between the hydride fuel cartridge and water tank module;

where hydride fuel of the hydride fuel cartridge is comprised of magnesium hydride,

where the hydrolysis reaction is based on an exothermic MgH_2 hydrolysis reaction pathway,

where fuel cartridge has the hydrogen storage capacity of 2.4 to 480 Wh, preferably 250 Wh to 350 Wh, more preferably 280 to 325 Wh, even more preferably around 300 Wh,

where the hydride fuel cartridge is comprised of a housing comprising a vacuum insulated double wall flask, a cover, a reactor manifold that contains all the essential fluidic/electrical/communication interfaces, temperature and pressure sensors, an electrically energized heating tube that is directly connected to a porous tube or porous structure for transferring and heating the water and then converting it into steam before introducing it into the magnesium hydride powder, porous tubes or porous structures to collect the generated hydrogen, and take the water out of the hydride fuel cartridge,

where the water tank module is comprised of the water storage tank medium, the water pump, a weighted clunk placed inside the water tank to transfer water to the hydride fuel cartridge in any orientation,

where fuel cartridge is hot-swappable and have quick-disconnect couplings at the fluidic interfaces for easy replacing,

where the hydrogen generation system controller manages the safe operation of the hydrogen generation system,

where the entire hydrogen generation system is assembled as a single module form,

where the battery is used to initiate the start-up sequence for the portable PEMFC apparatus, act as the primary power for the hydride reactor for the pre-heating period in order to start the hydrolysis reaction, and provide uninterruptable power during hot-swapping action of the hydride fuel cartridge,

where the casing's main function is to provide a form factor to integrate the fuel cell system and hydrogen generation inside a common housing,

where the pouch is used to carry the portable PEMFC apparatus over a soldier's body.

Claim 16. The apparatus according to Claim 15, further comprising

a main controller

the electromechanical connection is located on the main controller,

wherein the main controller is configured to manage the portable hydrogen PEMFC system,

wherein the main controller is configured to manage the hydrogen generation system.