

ELECTROCHEMICAL PNEUMATIC BATTERY

TECHNICAL FIELD

[0001] The present invention generally relates to pneumatics and hydraulics, and more particularly relates to an electrochemical pneumatic battery, such as an electrochemical pressure generator, providing a portable, untethered hybrid pneumatic/hydraulic solution.

BACKGROUND OF THE DISCLOSURE

[0002] Conventional pneumatic robotic grippers are tethered devices connected to existing pneumatic pressure generators, such as compressors, compressed-gas tanks, or pressurized gas supply lines. Accordingly, such grippers are only suitable for stationary operation with limited mobility. In contrast, sustained untethered operations necessitate on-board pressure generation using a pneumatic battery (i.e., pressure generator). A pressure generator should be compact, lightweight, quiet, safe (for both workers and the environment), and capable of producing high pressure. Conventional pneumatic batteries use mechanical compression, storage of pre-compressed gas, phase change materials, and chemical reactions. Among these conventional pneumatic batteries, chemical reaction-based pneumatic batteries show excellent compactness, lightweight, high power density, and low noise level. However, such batteries typically require performance of drastic reactions, such as explosive combustion and reactive gas decomposition, which are difficult to perform in a controllable and safe manner.

[0003] Compared to pure chemical reactions, electrochemical reactions are easier to control by electrical means and much safer. A typical electrochemical pressure generator is a hydrogen fuel cell which utilizes an electrochemical reaction based on

water electrolysis. In the high-pressure mode, the liquid water is split by a power source into gaseous hydrogen (H_2) and oxygen (O_2) on catalysts, leading to a drastic pressure increment in the pressure generator chamber. In the low-pressure mode, the gaseous hydrogen and oxygen recombine to liquid water spontaneously on different catalysts. However, the gaseous product (i.e., a H_2 - O_2 mixture) produced by such electrochemical pressure generator is explosive within the working parameters of the generator. To address this safety concern, a gas impermeable membrane (e.g., a proton-exchange membrane) is required to separate the produced hydrogen and oxygen gases. However, hydrogen gas cross-over (i.e., hydrogen leaking from the hydrogen compartment to the oxygen compartment) still occurs from time to time, especially at partial-load conditions (i.e., when the reaction does not proceed at a high rate) and upon membrane degrading (i.e., where oxygen gas gradually oxidizes the gas impermeable membrane). While partial load during the high-pressure mode can be mitigated by controlling the driving voltage source, membrane degradation is inevitable because the coexistence of oxygen and catalysts can produce highly oxidative reactive oxygen species, which will oxidize and degrade the membrane, thereby shortening the lifetime of the water electrolyzer.

[0004] Thus, there is a need for a safe, controllable, and high-pressure electrochemical pressure generator which overcomes the drawbacks of the prior art. Furthermore, other desirable features and characteristics will become apparent from the subsequent detailed description and the appended claims, taken in conjunction with the accompanying drawings and this background of the disclosure.

SUMMARY

[0005] According to at least one aspect of the present embodiments, a gas-reservoir electrochemical pressure generator is provided. The electrochemical pressure generator

includes an electrical power source, an electrochemical pressure generator, one or more gas reservoirs, and a hydraulic means. The electrochemical pressure generator is selectably connected to the electrical power source and the electrical power source is configured to power the electrochemical pressure generator in high-pressure mode operation to convert a solid state of hydrogen or oxygen within the electrochemical pressure generator into a high-pressure gas with a first pressure when connected thereto. The one or more gas reservoirs are in fluid communication with the electrochemical pressure generator and each includes a first chamber and a second chamber arranged in series. The first chamber of each of the one or more gas reservoirs is in fluid communication with the electrochemical pressure generator and includes a first surface of a non-rigid dividing element having a first area and the second chamber of each of the one or more gas reservoirs includes a second surface of the non-rigid dividing element having a second area mechanically connected to the first surface by the non-rigid dividing element to generate a second pressure. The hydraulic means is coupled to the second chamber and transmits the second pressure to a load.

[0006] According to another aspect of the present embodiments, a dual-gas-reservoir electrochemical pressure generator is provided. The system includes an electrical power source, an electrochemical pressure generator, a first gas reservoir, a second gas reservoir, a hydraulic means, a plurality of valves, and a control means. The electrochemical pressure generator is selectably connected to the electrical power source and the electrical power source is configured to power the electrochemical pressure generator to produce a high-pressure gas with first pressure P1 from a solid state of hydrogen or oxygen within the electrochemical pressure generator. The electrochemical pressure generator is also configured to convert the high-pressure gas into a solid state of the hydrogen or the oxygen resulting in a second pressure P2. The

first gas reservoir is in fluid communication with the electrochemical pressure generator and includes a first chamber and a second chamber arranged in series. The first chamber is in fluid communication with the high-pressure gas having the first pressure and includes a first surface on a first non-rigid dividing element separating the first chamber from the second chamber, the first surface having an area S_1 . The second chamber is filled with a non-compressible fluid and includes a second surface of the non-rigid dividing element having an area S_1' to generate a pressure P_1' , wherein $S_1 > S_1'$ and $P_1 < P_1'$. The second gas reservoir is in fluid communication with the electrochemical pressure generator and includes a third and fourth chamber arranged in series. The third chamber is in fluid communication with gas having the second pressure P_2 and includes a third surface of a second non-rigid dividing element separating the third chamber from the fourth chamber, the third surface having an area S_2 . The fourth chamber is filled with a non-compressible fluid and includes a fourth surface having an area S_2' in contact with the third surface to output a pressure P_2' , wherein $S_2 < S_2'$ and $P_2 > P_2'$. The hydraulic means is selectably coupled to the second chamber and the fourth chamber for transmitting the pressure P_1' and the pressure P_2' to a load. The plurality of valves control flow of gas from the electrochemical pressure generator to the first and third chambers and control the flow of pressure from the second and fourth chambers to the hydraulic means. And the control means is coupled to the plurality of valves and configured for controlling transmission of the pressure P_1' and the pressure P_2' to the load.

BRIEF DESCRIPTION OF THE DRAWINGS

[0007] The accompanying figures, where like reference numerals refer to identical or functionally similar elements throughout the separate views and which together with

the detailed description below are incorporated in and form part of the specification, serve to illustrate various embodiments and to explain various principles and advantages in accordance with present embodiments.

[0008] FIG. 1 depicts a schematic illustration of a first variation of an electrochemical pressure generator in accordance with present embodiments.

[0009] FIG. 2 depicts a schematic illustration of a second variation of an electrochemical pressure generator in accordance with the present embodiments.

[0010] FIG. 3, comprising FIGs. 3A and 3B, depicts illustrations of bellows for use as expandable gas reservoirs in the electrochemical pressure generator of FIG. 1 or FIG. 2 in accordance with the present embodiments, wherein FIG. 3A depicts a side planar view of the bellows and FIG. 3B depicts a bottom side perspective view of the bellows.

[0011] FIG. 4 depicts an illustration of an oxygen-based electrochemical pressure generator reaction in accordance with the present embodiments at two different states.

[0012] And FIG. 5 depicts a hydrogen-based electrochemical pressure generator reaction in accordance with the present embodiments.

[0013] Skilled artisans will appreciate that elements in the figures are illustrated for simplicity and clarity and have not necessarily been depicted to scale.

DETAILED DESCRIPTION

[0014] The following detailed description is merely exemplary in nature and is not intended to limit the invention or the application and uses of the invention. Furthermore, there is no intention to be bound by any theory presented in the preceding background of the invention or the following detailed description. It is the intent of present embodiments to present an electrochemical pressure generator having many advantages over prior art electrochemical pressure generators.

[0015] The adoption of fluidic actuation, despite its advantages over electrical actuation, is hindered in many fields because of its low portability due to the need of heavy and bulky accessories, such as pumps and compressors. Electrochemical pressure generators are high-pressure pneumatic batteries with direct energy conversion from electrical to mechanical domain without any need for pumps and compressors and can significantly broaden the application of fluidically actuated devices and robots.

[0016] The electrochemical pressure generator in accordance with present embodiments is fluidically untethered, i.e. with no need for connections to external pressure generators. Thus, the electrochemical pressure generator in accordance with the present embodiments is self-contained for easier deployability in practical scenarios with minimal logistic impact. In addition, the electrochemical pressure generator in accordance with the present embodiments is compact and lightweight due to the electric energy being directly converted into mechanical energy with no need for motors, pumps or compressors, leading to great portability and adaptability as well as quiet operation and absence of vibrations.

[0017] Also, the electrochemical pressure generator in accordance with the present embodiments provides a high pressure which is much higher than that provided by typical compressed gas lines resulting in a unique advantage for robotic devices. For example, in the case the actuator is a gripper, the high pressure provided in accordance with the present embodiments leads to substantial gripping force, even with small grippers, which is needed for a true conformal contact with the object being gripped.

[0018] Further, the electrochemical pressure generator in accordance with the present embodiments is safe since only small amounts of high-pressure gas is produced as needed, with no storage of large amounts of high-pressure gases or explosive gas mixtures. In addition, the electrochemical pressure generator in accordance with the

present embodiments only involves gas and solid-state materials without liquid materials, which makes the performance stable regardless of the orientation of the electrochemical pressure generator. Also, the operation is fast thanks to the adoption of the hybrid pneumatic/hydraulic solution: pressure is generated in the form of a compressed gas, while power transmission from the electrochemical pressure generator to the gripper is hydraulic, thus reducing the dead volume occupied by compressible fluids and consequently reducing the latency in building up the pressure. Operation is also clean and green, because there is no chemical or gas discharged into the environment, e.g. to restore a low pressure, there is no electromagnetic noise due to the power source being direct current, and there is no mechanical noise or vibration.

[0019] Further, the electrochemical pressure generators in accordance with the present embodiments are able to serve as a universal portable pressure generator, which can drive various robotic devices that need fluidic actuation. For example, the electrochemical pressure generators in accordance with the present embodiments can be used to drive autonomous and bioinspired robotic devices, surgical robotic devices for steering robotic endoscopes or actuate surgical tools, wearable robotic devices such as exoskeletons for assisting elderly or neurological patients, wearable systems for human augmentation such as industrial systems for heavy-duty tasks, and haptic devices such as wearable systems for force rendering.

[0020] Referring to FIG. 1, a schematic illustration 100 depicts a first variation of an electrochemical pressure generator in accordance with the present embodiments. The electrochemical pressure generator includes a reactor 110 and a pressure amplifier or intensifier 150. Referring to the reactor 110, an electrochemical pressure generation method leverages on a single gas (e.g., hydrogen or oxygen) coupled with a transition metal oxyhydroxide via an electrochemical reaction. The reactor 110 is a rigid chamber

which includes a top electrode 112 (preferably a metal electrode), a bottom electrode 114 (preferably a carbon electrode with a gas permeable structure) and a solid electrolyte 116 sandwiched therebetween. The structure of the rigid chamber may be formed of a metal frame with chemically resistive and electrically insulative (e.g., Teflon®) coating of the inner surface. A power source 120 is selectably couplable to the top electrode 112 and the bottom electrode 114 for providing power thereto. During a high-pressure mode, the electrochemical pressure generator is driven by the power source 120 coupled between the top electrode 112 and the bottom electrode 114 to produce a high-pressure gas (hydrogen or oxygen) from the electrolyte 116 that passes through the permeable structure of the bottom electrode 114 and a gas-permeable hydrophobic film 118 to be stored in a gas reservoir 152 with a first pressure, P1.

[0021] The electrochemical reactor 110 does not need an external power source to drive it in the low-pressure mode. The reaction is automatic and generates electricity. In the low-pressure mode, the reactor 110 is connected to an electric energy storage device 122. Any electric energy storage device 122 can be used, such as a battery, capacitor, supercapacitor, or hybrid battery-capacitor. In this low-pressure mode, the pressure P1 decreases as gas is converted back to solid, while the electrochemical pressure generator charges the energy storage device 122, regenerating part of the energy consumed from power source 120 during the high-pressure mode. The energy stored in the energy storage device 122 can be re-used by the power source 120 during high-pressure mode.

[0022] Note that the energy generated during the low-pressure mode can be stored in the power source 120 as well. For example, the power source 120 may comprise a stack of three batteries, and the energy storage device 122 can be one of the three batteries.

A computer means (not shown) can be used to facilitate the control and charging of the electric energy storage device 122 during the low-pressure mode.

[0023] The pressure intensifier 150 is mounted in series to the electrochemical reactor 110. The pressure intensifier 150 includes a first chamber, the gas reservoir 152, and a second chamber 160. Each chamber is in mechanical contact with one side of a non-rigid dividing element 154. The two contact surfaces of the gas reservoir 152 and the second chamber 160 with the non-rigid dividing element 154 have different areas, the former being larger than the latter to achieve pressure intensification. The gas reservoir 152 (i.e., the first chamber) is in fluid communication with the gas produced by the electrochemical pressure generator and has a surface area S_1 on the non-rigid dividing element 154, while the second chamber 160 has a surface S_1' on the non-rigid dividing element 154. The pressure P_1 exerts on the surface S_1 of the non-rigid dividing element 154, which in turn is in mechanical contact with the surface S_1' of the non-rigid dividing element 154 exerting a pressure P_1' . If the stiffness of the two chambers 152 and 160 is negligible, the pressure P_1 will be amplified to P_1' , where $P' = P_1 \cdot S_1 / S_1'$, resulting in a larger output pressure if S_1 is larger than S_1' . As such, the output pressure P_1' is controlled by the power source 120 according to the requirements of the application. In a preferred embodiment, both the first chamber 152 and the second chamber 160 are realized using bellows as shown in FIGs. 3A and 3B. The artisan skilled in the art can immediately understand that one or both bellows can be replaced by other equivalent means, including, for example, pistons, rolling diaphragm pistons and combinations thereof, as well as the number of bellows and pistons on either side of the non-rigid dividing element 154.

[0024] Further, the second chamber 160 can conveniently be filled with a non-compressible fluid, such as silicone or mineral oil, or even water. In this way, the

pneumatically generated pressure is transmitted to a load via a hydraulic means, thus reducing the dead volume of the fluidic path and increasing the responsiveness of the system in terms of capability to change the output pressure as a function of the change of the input pressure generated by the electrochemical pressure generator.

[0025] The advantages of the first embodiment as pictured in the illustration 100 are compactness and small size. However, the rate of pressure increase and decrease (i.e., charging and discharging of the pressure generator) is limited by the reaction kinetics of the low-pressure mode (discharging process). In order to increase the charging/discharging rate and, therefore, the overall working frequency of the electrochemical pressure generator, a second variation of an electrochemical pressure generator in accordance with the present embodiments is depicted in a schematic illustration 200 of FIG. 2. The electrochemical pressure generator of the illustration 200 includes the reactor 110 and works in a very similar way as that of the first variation of the illustration 100 (FIG. 1), except with a newly introduced pressure reservoir, i.e., a third chamber 252. The third chamber 252 is arranged in series and in mechanical contact with a fourth chamber 260. This arrangement of the third chamber 252 and the fourth chamber 260 can be positioned fluidically in parallel to the first chamber 152 and the second chamber 160. Further, the third chamber 252 is in fluid communication with the gas in the reactor 110 of the electrochemical pressure generator and has a surface S2 on a non-rigid dividing element 254. During high-pressure mode, the electrochemical pressure generator, which is driven by the power source 120, produces a high-pressure gas that is stored in the high-pressure reservoir (i.e., the first chamber 152 with pressure P1). During low-pressure mode, the electrochemical pressure generator decreases the pressure P2 in the third chamber 252 by converting the gas in

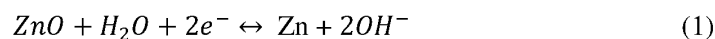
the third chamber 252 back into the electrolyte 116, and then stores the low-pressure gas in the low-pressure reservoir (i.e., the third chamber 252 with pressure P2).

[0026] In the low-pressure mode, the electrochemical pressure generator charges the energy storage device 122, regenerating part of the energy consumed in the high-pressure mode by the power source 120. The pressure P2 is exerted on the surface S2 of the non-rigid dividing element 254. The resulting force is counterbalanced by the pressure P2' applied to the surface S2' of the fourth chamber 260 on the other side of the non-rigid dividing element 254. Computer-controlled valves 270 and 275 can be installed at the connections between the reactor 110 and the first chamber 152 and the third chamber 252, respectively, to automatically select the high-pressure or low-pressure mode based on the pressure feedback from the reservoirs (or the chambers 152, 252). The electrochemical pressure generator keeps working to maintain the pressures P1 and P2 and, as a result, the stored high-pressure and low-pressure gases are always available for use at outlet valves 280 and 285, respectively, to be transmitted to a load via a hydraulic means.

[0027] Referring to FIG. 3A, a side planar view 300 depicts a bellows 310 for use as any or all of the first chamber 152, the second chamber 160, the third chamber 252 or the fourth chamber 260. A bottom side perspective view 350 of the bellows 310 is depicted in FIG. 3B. The bellows 310 are preferable for the first chamber 152, the second chamber 160, the third chamber 252 and/or the fourth chamber 260 as the bellows 310 can expand and contract longitudinally with minimal radial deformation. It is understood that all or some of the bellows can be replaced with pistons, rolling diaphragm pistons or their combinations.

[0028] An oxygen-based electrochemical pressure generator reaction is depicted in the illustration 400 of FIG. 4. In the high-pressure mode, zinc oxide (ZnO) or hydroxide

[Zn(OH)₂] is reduced to zinc metal via Equation 1 on zinc metal electrode (cathode) while producing hydroxide ions (OH⁻).



The OH⁻ ions transport across the solid electrolyte 116 (e.g., a potassium hydroxide gel) and get oxidized on an anode (e.g., the carbon electrode 114) to produce oxygen gases (O₂), which will increase the pressure. The overall reaction is shown in Equation 2.

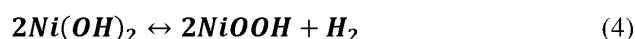


[0029] The anode can also be any stable metal anode such as nickel anode. In the low-pressure mode, Zn is oxidized to Zn(OH)₂ or ZnO on the anode while O₂ is reduced to OH⁻ ions on the cathode, resulting in a decrease of pressure. The overall low-pressure reaction is shown in Equation 3.



[0030] The ions are confined in the solid gel electrolyte 116. The super-hydrophobic gas-permeable membrane 118 is used to confine the water molecules in the reactor 110 while allowing the gas to transport in and out of the reactor 100. The trace amount of hydrogen gas generated on the Zn cathode during the high-pressure mode from the parasitic reaction (hydrogen evolution reaction) is released to the environment through a hydrogen-permeable membrane 124 (e.g., a microporous silicon dioxide membrane) shown in FIG. 1 and FIG. 2 that allows the passage of hydrogen gas while stopping the passage of oxygen gas. This greatly enhances the safety of the electrochemical pressure generator by avoiding the generation of a hydrogen-oxygen mixture. The oxygen-based electrochemical generation is safe; however, the oxygen reduction reaction has slow kinetics which limits the speed of the gas consumption.

[0031] Accordingly, a hydrogen-based electrochemical pressure generation method is presented in the illustration 500 of FIG. 5. In the high-pressure mode, nickel hydroxide $[\text{Ni}(\text{OH})_2]$ is oxidized to nickel oxyhydroxide (NiOOH) on a nickel anode while water is reduced to hydrogen on the cathode. The cathode can be a platinum-coated carbon electrode 114. As a result, the pressure increases. The overall reaction is shown in Equation 4.



In the low-pressure mode, the NiOOH is reduced to $\text{Ni}(\text{OH})_2$ on nickel anode, and H_2 is oxidized to water on the cathode. Consequently, the pressure decreases. The overall reaction is shown in Equation 5.



[0032] Hydrogen is difficult to confine especially at high pressure. Therefore, it is expensive to construct a hydrogen-based electrochemical pressure generator. However, the hydrogen reduction/oxidation kinetics are much faster than those of oxygen, thus offering a fast speed of gas generation and consumption, resulting in a fast charge/discharge of the pneumatic battery (i.e., pressure generator). Moreover, a hydrogen molecule needs two electrons, half of the four electrons needed for an oxygen molecule. Accordingly, a hydrogen-based electrochemical pressure generator is much more efficient than an oxygen-based electrochemical pressure generator.

[0033] The electrochemical reaction in accordance with the present embodiments are not limited to Zn-ZnO or $\text{Ni}(\text{OH})_2\text{-NiOOH}$, as they may include many metal-metal oxide/hydroxide/oxyhydroxide couples such as iron, cobalt, aluminum, magnesium, potassium, calcium, sodium, tin, lithium, as well as non-metal elements such as silicon. In addition, more than one metal can be employed in accordance with the present embodiments such as $\text{NiCo}(\text{OH})_2/\text{NiCoOOH}$, and $\text{NiFeCo}(\text{OH})_2/\text{NiFeCoOOH}$.

[0034] A comparison of the advantages of the present embodiments and state-of-the-art pressure generators is summarized in TABLE 1. Compared to traditional pressure generation by a centralized compressor followed by distribution means to a working site using a gas pipe, the electrochemical pressure generator is smaller, safer, and much quieter. Moreover, the electrochemical pressure generator is portable, and it is able to generate higher pressure than the commonly used five- to six-bar gas pipe. In comparison with the state-of-the-art chemical and electrochemical generators, the electrochemical pressure generator in accordance with the present embodiments is safer, due to the single-gas operation, and more efficient, due to the regenerative low-pressure mode.

Parameters	Traditional pressure generator	The state-of-the-art chemical/electrochemical pressure generator	The present invention
type	Pneumatic/hydraulic	Pneumatic	Pneumatic/hydraulic
Size	Large	Small	Small
Untethered (standalone)	No	Yes	Yes
Pressure	< 5-6 bar	< 5-6 bar	$\geq$ 5-6 bar
Portability	Poor	Excellent	Excellent
Safety	Good	Discrete	Excellent
Noise level	noisy due to compressor/motor	Quiet	Quiet

TABLE 1

[0035] The adoption of fluidic actuation, despite its advantages over electrical actuation, is now hindered in several fields because of its low portability, due to the need of heavy and bulky accessories, such as pumps and compressors. High-pressure pneumatic batteries in accordance with the present embodiments with direct energy conversion from electrical to mechanical domain, without any need for pumps and compressors, can significantly broaden the application of fluidically actuated devices

and robots. One industrial application is the powering of fluidically-actuated robotic grippers. However, the electrochemical pressure generator in accordance with the present embodiments also holds promise of allowing the development of fully untethered fluidically actuated systems in general. Therefore, besides the industrial automation one, the electrochemical pressure generator would benefit autonomous and bioinspired robotics, surgical robotics, wearable robotics and haptic systems. In summary, the self-contained, electrically driven, portable pressure generator in accordance with the present embodiments will have an important impact on several branches of robotics and automation where the adoption of efficient, lightweight, quiet and compact actuation means is acknowledged as beneficial.

[0036] Thus, it can be seen that the present embodiments provide a safe, controllable, high-speed and high-pressure electrochemical pressure generator which is self-contained for easier deployability in practical scenarios with minimal logistic impact. In addition, the present embodiments provide an electrochemical pressure generator which is compact and lightweight due to the electric energy being directly converted into mechanical energy with no need for motors, pumps or compressors, leading to great portability and quiet operation. The present embodiments also provide an electrochemically generated high pressure which is much higher than provided by typical compression gas lines resulting in a unique advantage for robotic devices. Further, the present embodiments provide clean and green operation because there is no chemical or gas discharge into the environment and there is no electromagnetic noise, due to the power source being direct current, and no acoustic noise, due to the lack of motors, compressors or pumps.

[0037] While exemplary embodiments have been presented in the foregoing detailed description of the present embodiments, it should be appreciated that a vast number of

variations exist. It should further be appreciated that the exemplary embodiments are only examples, and are not intended to limit the scope, applicability, operation, or configuration of the invention in any way. Rather, the foregoing detailed description will provide those skilled in the art with a convenient road map for implementing exemplary embodiments of the invention, it being understood that various changes may be made in the function and arrangement of steps and method of operation described in the exemplary embodiments without departing from the scope of the invention as set forth in the appended claims.