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Systems and methods for hydrogen recovery

Abstract

A system for hydrogen recovery includes a dryer having an inlet that may be fluidly connected to a hydrogen outlet of a hydrogen generator, a hydrogen using device having an inlet fluidly connected to a dry hydrogen outlet of the dryer, and one or more conduits fluidly connecting a wet hydrogen outlet from the dryer and an impure hydrogen exhaust outlet of the hydrogen using device to the inlet of the dryer.

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Background/Summary

CROSS-REFERENCE TO RELATED APPLICATIONS (1) This application claims priority to TW Application No. 111125595 entitled “SYSTEMS AND METHODS FOR HYDROGEN RECOVERY”, filed Jul. 7, 2022, and also claims priority to U.S. Provisional Application No. 63/221,664 entitled “ELECTROLYZER SYSTEM WITH HYDROGEN RECOVERY” filed Jul. 14, 2021, the entire contents of which are incorporated by reference herein.

FIELD

(1) The present disclosure is directed to chemical production in general and, more specifically, to systems for hydrogen recovery.

BACKGROUND

(2) Hydrogen is a common gas that has many industrial uses, such as petroleum refining, metal treatment, food processing, and ammonia production. Although hydrogen is abundant and can be formed from a variety of renewable and non-renewable energy sources, the combustibility of hydrogen in air makes hydrogen difficult to store and ship. As a result, hydrogen is generally not amenable to large-scale production at a centralized facility for subsequent distribution across large geographical regions. Rather, hydrogen is generally used at or near the site of its production.

(3) Co-locating hydrogen production with its ultimate industrial use can present challenges related to plant footprint, safety, and resource availability. Accordingly, there remains a need for hydrogen generation that can be carried out cost-effectively in small footprint plants that are amenable to safe implementation in a wide range of locations, including resource-constrained areas.

SUMMARY

(4) Provided herein is a system for hydrogen recovery. The system a dryer comprising an inlet that may be fluidly connected or operably connected to a hydrogen generator, and a hydrogen-using application comprising an inlet fluidly connected to a dry hydrogen outlet of the dryer and an outlet fluidly connected to the inlet of the dryer. In some embodiments, the hydrogen generator comprises an electrolyzer stack. In preferred embodiments, the inlet of the dryer is fluidly connected to the hydrogen generator.

(5) In some embodiments, the system comprises one or more pumps. In some aspects, each of the pumps comprises an inlet fluidly connected to the hydrogen-using application and an outlet fluidly connected to the inlet of the dryer. In some additional aspects, the dryer further comprises a wet hydrogen outlet fluidly connected to the inlet of at least one of the one or more pumps.

(6) In some embodiments, the system comprises one or more humidifiers. In some aspects, each of the one or more humidifiers comprising an inlet and an outlet, the outlet fluidly connected to the one or more pumps.

(7) In some embodiments, the system comprises a purifier. In some aspects, the purifier comprises an inlet fluidly connected to the dry hydrogen outlet of the dryer and an outlet fluidly connected to the inlet of the hydrogen-using application.

(8) In some embodiments, the system further comprises at least one oxygen sensor.

(9) In some embodiments, the dryer further comprises a wet hydrogen outlet fluidly connected to the inlet of the dryer.

(10) In some embodiments, the system further comprises a blending tank. In some aspects, the blending tank comprises an inlet fluidly connected to the outlet of the hydrogen-using application.

(11) Further provided herein are methods for generating and recovering hydrogen. The method comprises providing a wet hydrogen stream from a hydrogen generator to an inlet of a dryer, outputting a dry hydrogen stream from a first outlet of the dryer to a hydrogen-using application,

providing a purge wet hydrogen stream from a second outlet of the dryer to the inlet of the dryer, and providing an exhaust hydrogen stream from the hydrogen-using application to the inlet of the dryer. In some embodiments, the hydrogen generator comprises an electrolyzer stack.

(12) In some embodiments, providing the exhaust hydrogen stream from the hydrogen-using application to the inlet of the dryer may be accomplished by one or more pumps.

(13) In some embodiments, the method further comprises humidifying the exhaust hydrogen stream from the hydrogen-using application before providing the exhaust hydrogen stream from the hydrogen-using application to the inlet of the dryer.

(14) In some embodiments, the method further comprises purifying the dry hydrogen stream from the first outlet of the dryer before outputting the dry hydrogen stream from the first outlet of the dryer to the hydrogen-using application. In some aspects, the purifying is accomplished via a purifier. In some exemplary embodiments, the method further comprises humidifying a purge wet hydrogen stream from an outlet of the purifier.

(15) In some embodiments, the method further comprises combining the exhaust hydrogen stream from the hydrogen-using application and the purge wet hydrogen stream from the second outlet of the dryer prior to providing the exhaust hydrogen stream from the hydrogen-using application and the purge wet hydrogen stream from the second outlet of the dryer to the inlet of the dryer. In some aspects, the combining is accomplished via a blending tank. In some further aspects, the method further comprises humidifying the combined exhaust hydrogen stream from the hydrogen-using application and the purge wet hydrogen stream from the second outlet of the dryer prior to providing the exhaust hydrogen stream from the hydrogen-using application and the purge wet hydrogen stream from the second outlet of the dryer to the inlet of the dryer.

Description

BRIEF DESCRIPTION OF THE FIGURES

(1) FIG. 1A is a perspective view of a system including a cabinet and an electrochemical module.

(2) FIG. 1B is a block diagram of the system of FIG. 1A, representing connection of the electrochemical module to a water circuit and a hydrogen circuit in the cabinet.

(3) FIG. 2A is a schematic representation of an electrochemical stack of the electrochemical module of the system of FIGS. 1A and 1B.

(4) FIG. 2B is a top view of an anode side of a bipolar plate of the electrochemical stack of FIG. 2A.

(5) FIG. 2C is a top view of a cathode side of the bipolar plate of FIG. 2B.

(6) FIG. 3A is a perspective view of the electrochemical module of the system of FIGS. 1A and 1B, shown with a liquid-management section and a gas-management section of the electrochemical module shown coupled to one another.

(7) FIG. 3B is a partial exploded view of the electrochemical module of the system of FIGS. 1A and 1B, shown with the liquid-management section and the gas-management section of the electrochemical module decoupled from one another.

(8) FIGS. 4A and 4B are block diagrams of exemplary systems of the present disclosure.

(9) Like reference symbols in the various drawings indicate like elements.

DETAILED DESCRIPTION

(10) Provided herein are systems for recovering hydrogen in a hydrogen generation system. The systems of the present disclosure generally comprise a hydrogen generator, a dryer, and a hydrogen-using application. The hydrogen-using application may be any hydrogen-using device or process, such as a glass float furnace, a metals furnace, or other processes devices requiring hydrogen. In some embodiments, the system may comprise a plurality of hydrogen-using applications. Once the hydrogen is used by the hydrogen-using application, the exhaust hydrogen is

recycled back into the system for purification and further use, thereby increasing the overall efficiency of the system.

(11) The hydrogen generator may comprise any device or system capable of generating hydrogen gas. The hydrogen generator may comprise an electrolyzer stack, a steam methane reformer, a methane pyrolysis system, a plasma reforming system, or other devices and systems known in the art for producing hydrogen. In some embodiments, the system of the present disclosure may comprise more than one hydrogen generator.

(12) Preferably, the hydrogen generator comprises an electrolyzer stack. The electrolyzer stack may be any electrolyzer stack known in the art capable of producing hydrogen from water. Generally, the electrolyzer stack comprises an inlet fluidly connected to a water source (e.g., tap water, distilled water, etc.), which is operable to receive water. The electrolyzer stack further comprises an outlet fluidly connected to an inlet of a dryer. A stream of wet hydrogen flows from the electrolyzer outlet to the inlet of the dryer. Those having skill in the art will appreciate that the moisture content of the wet hydrogen flowing from the electrolyzer will depend on the parameters of the electrolyzer, the pressure of the hydrogen stream, the temperature of the hydrogen stream, and the partial pressure of the wet hydrogen as compared to the total pressure of the system. As a non-limiting example, a wet hydrogen stream exiting the electrolyzer stack at 40° C., the moisture content of the wet hydrogen may be about 2 mol %. Preferred electrolyzer stacks for use in the systems of the present disclosure are described in more detail below and in U.S. application Ser. No. 17/101,232 entitled “ELECTROCHEMICAL DEVICES, MODULES, AND SYSTEMS FOR HYDROGEN GENERATION AND METHODS OF OPERATING THEREOF” filed on Nov. 23, 2020, the entire contents of which are incorporated by reference herein.

(13) The dryer is operable to separate water from a wet hydrogen stream, thereby forming a dry hydrogen stream. Dryers suitable for drying the wet hydrogen stream are well-known by those having ordinary skill in the art, and may include dehumidifiers or other heat exchangers known in the art. The dryer comprises an inlet that is capable of being fluidly connected or operable connected to the hydrogen generator, and an outlet fluidly connected to a hydrogen-using application. In preferred embodiments, the inlet is fluidly connected and/or operably connected to the hydrogen generator. The outlet fluidly connected to the hydrogen-using application is operable to deliver a dry hydrogen stream to the hydrogen-using application; therefore, the outlet comprises dry hydrogen. In some embodiments, the system may comprise a plurality of dryers connected in parallel.

(14) The dryer may further comprise a second outlet operable to deliver a purge wet hydrogen stream from the dryer. The purge wet hydrogen stream may be fluidly connected to the inlet of the dryer, a pump, to a blending tank, or to another unit in the system.

(15) The system may further comprise a purifier to remove more water and other impurities from the hydrogen, thereby providing a purified hydrogen stream. The purifier may comprise an inlet that may be fluidly connected to the outlet of the dryer. The purifier may further comprise a first outlet that is fluidly connected to the inlet of the hydrogen-using application. The first outlet from the purifier comprises purified hydrogen. The purifier may further comprise a second outlet that is fluidly connected to a blending tank, a pump, a humidifier, and/or another process unit requiring a wet hydrogen stream. The second outlet of the purifier comprises a purge wet hydrogen stream. In some embodiments, the system may comprise a plurality of purifiers connected in parallel. The purifier may include a pressure swing adsorption purifier, a palladium diffuser, a PEM electrolyzer purifier, a silica desiccant purifier, or other hydrogen purification methods known in the art. In preferred embodiments, the purifier comprises a pressure swing adsorption purifier.

(16) The system may further comprise one or more pumps to increase the pressure of the hydrogen exhaust stream from the hydrogen-using application before the hydrogen enters the inlet to the dryer. The one or more pumps may be any pumps or compressors known in the art operable to increase the pressure of the hydrogen. Preferably, the one or more pumps comprises an

electrochemical pump, such as a proton exchange membrane disposed between an anode and a cathode. The pump may produce a wet hydrogen stream and a purge water stream.

(17) The system may further comprise one or more humidifiers. Additionally, some electrochemical hydrogen pumps and driers may require humidified hydrogen for proper function. The humidifiers may be operable to add water to the hydrogen exhaust stream from the hydrogen-using application prior to recycling the hydrogen back into the inlet of the dryer. Preferably, the one or more humidifiers is fluidly connected to one or more pumps such as electrochemical hydrogen pumps. Each humidifier may comprise an inlet and an outlet. The inlet of the humidifier may be fluidly connected to the purifier, the exhaust hydrogen stream from the application, or to another process unit comprising a dry or purified hydrogen stream. The outlet of the humidifier comprises wet hydrogen. The outlet of the humidifier may be fluidly connected to a pump, to the inlet of the dryer, or to another process unit requiring a wet hydrogen stream.

(18) The system may further comprise an oxygen sensor. The oxygen sensor is operable to detect the concentration of oxygen in a hydrogen stream. The oxygen sensor may be operably connected to a valve and a controller, wherein when an abnormal level of oxygen is detected the controller may automatically close the valve to stop the gas flow. Alternatively, or additionally, the oxygen-rich gas stream may be purged, scrubbed, or vented to the environment to remove the oxygen from the system. In some embodiments, the system may comprise a plurality of oxygen sensors located throughout the system to monitor the flow of oxygen through the system.

(19) The system may further comprise a blending tank. The blending tank is operable to combine various streams of hydrogen into a homogeneous stream. Blending tanks are generally known in the art, and may include static mixers, in-line mixers, mixing tanks, etc. The blending tank may comprise an inlet fluidly connected to the exhaust hydrogen stream from the hydrogen-using application, the purge wet hydrogen stream from the dryer, the purge wet hydrogen stream from the purifier, and/or another process unit. The outlet of the blending tank may be fluidly connected to a humidifier, a pump, or another process unit. In some embodiments, the system may comprise a plurality of blending tanks.

(20) The systems will now be described more fully hereinafter with reference to the accompanying figures, in which exemplary embodiments are shown. The foregoing may, however, be embodied in many different forms and should not be construed as limited to the exemplary embodiments set forth herein. All fluid flows may flow through conduits (e.g., pipes and/or manifolds) unless specified otherwise. It will be appreciated by those having ordinary skill in the art that valves, sensors, and other instrumentation may be included in any of the systems described herein.

(21) In the description that follows, various aspects of electrochemical devices, modules, and systems are described in the context of electrochemical electrolysis of hydrogen from water and electricity with separately ventilated cabinet sections (i.e., spaces) for electrolysis (i.e., electrolyzer stack location), oxygen processing and hydrogen processing. This configuration increases the system safety by separating oxygen and hydrogen processing equipment into separately ventilated spaces to reduce the likelihood of mixing and exothermic reaction between leaking oxygen and hydrogen.

(22) Nevertheless, unless otherwise specified or made clear from the context, it shall be understood that any one or more of the various different devices, modules, or systems described herein may be additionally, or alternatively, used in any one or more of various different electrochemical processes in which a lower pressure reactant is an input to an electrochemical process that produces a higher-pressure product. For example, unless a contrary intent is indicated, any one or more of the various different devices, modules, and systems described herein may be used to electrochemically pump hydrogen, as may be useful for recirculating hydrogen to increase the overall yield of a chemical process. As a more specific example, any one or more of the various different devices, modules, and systems described herein may be used to generate hydrogen and/or recirculate hydrogen for ammonia synthesis as part of any one or more of the various systems and

methods described in U.S. patent application Ser. No. 17/101,224 entitled “SYSTEMS AND METHODS OF AMMONIA SYNTHESIS” filed Nov. 23, 2020, and U.S. patent application Ser. No. 17/101,232 entitled “ELECTROCHEMICAL DEVICES, MODULES, AND SYSTEMS FOR HYDROGEN GENERATION AND METHODS OF OPERATING THEREOF,” filed Nov. 23, 2020, and U.S. patent application Ser. No. 17/101,251 entitled “MODULAR SYSTEMS FOR HYDROGEN GENERATION AND METHODS OF OPERATING THEREOF” filed Nov. 23, 2020, the entire contents of each of which are incorporated herein by reference.

(23) Referring now to FIGS. 1A and 1B, a system **100** for generating hydrogen may include an electrochemical module **102** and at least one cabinet **104**. The at least one cabinet **104** may define a first volume **106a**, a second volume **106b**, and a third volume **106c** that are each isolated from one another, except for fluid connections between the electrochemical module **102** in the second volume **106b** and equipment in the first volume **106a** and the third volume **106c**. While one cabinet (i.e., housing) **104** with three isolated volumes (**106a**, **106b**, **106c**) is shown in FIG. 1A, it should be noted that two or three separate cabinets **104** each containing one or two of the three isolated volumes may be used instead. If a single cabinet **104** is used, then the adjacent isolated volumes are isolated from each other by internal walls or partitions **105a**, **105b** of the cabinet **104**. For example, a first internal wall **105a** may separate the first volume **106a** from the second volume **106b**, and a second internal wall **105b** may separate the second volume **106b** from the third volume **106c**. As used herein, two volumes are isolated from each other if a gas in one volume cannot pass into the other volume except through designated fluid conduits (e.g., pipes or manifolds) that connect the two volumes and are configured to provide a gas or a liquid between the two volumes. In one embodiment, each of the volumes **106a**, **106b** and **106c** is separately ventilated by separate dedicated ventilation equipment, as will be described in more detail below.

(24) The electrochemical module **102** may include an electrolyzer module, such as a proton exchange membrane (PEM) based electrolyzer module. The module **102** may include one or more electrochemical stacks **200**, such as one or more PEM based electrolyzer stacks. The module **102** may also include a plurality of first fluid connectors **110a,b** (referred to collectively as the plurality of first fluid connectors **110a,b** and individually as the first fluid connector **110a** and the first fluid connector **110b**), and a second fluid connector **112**. As described in greater detail below, the electrochemical module **102** may be disposed in the second volume **106b** (e.g., between the first volume **106a** and the third volume **106c**) and connected in fluid communication with a water circuit **114** in the first volume **106a** via the plurality of first fluid connectors **110a,b** and in fluid communication with a hydrogen circuit **116** in the third volume **106c** via the second fluid connector **112**. Such partitioning of the electrochemical module **102**, the water circuit (which includes oxygen processing equipment) **114**, and the hydrogen circuit **116** into respective volumes **106b**, **106a**, **106c** which are isolated from one another within the one or more cabinets **104** may facilitate safely generating commercial-scale quantities of hydrogen within a spatially compact footprint. This may be useful for, among other things, using the system **100** to generate hydrogen at installations with limited space and/or transporting the system **100** to remote installation sites. Additionally, or alternatively, as also described in greater detail below, the connectivity between the electrochemical module **102** and each of the water circuit **114** and the hydrogen circuit **116** within the cabinet **104** may include modularity that facilitates installation, maintenance, and repair.

(25) In use, as described in greater detail below, water and electricity may be provided to the electrochemical stack **200**, where some of the water may be electrochemically electrolyzed to form hydrogen (e.g., via hydrogen ion diffusion through a PEM electrolyte from an anode side of the electrolyzer cell to the cathode side of the PEM electrolyzer cell). For example, the water circuit **114** may be actuatable to deliver purified water from the first volume **106a** of the cabinet **104** to the electrochemical stack **200** in the second volume **106b** of the cabinet **104** via the first fluid coupling. As the purified water moves through the electrochemical stack **200**, power delivered to the electrochemical stack **200** may move protons of at least some of the purified water through the

PEM electrolyte to form hydrogen. Oxygen formed on the anode side of the cell by the electrolysis of the purified water, along with excess purified water, may be returned from the electrochemical stack **200** in the second volume **106b** to the water circuit **114** in the first volume **106a**. Additionally, or alternatively, the hydrogen formed by electrolysis in the electrochemical stack **200** may move from the cathode side of the electrochemical stack **200** in the second volume **106b** of the cabinet **104** to the hydrogen circuit **116** in the third volume **106c** of the cabinet **104**. Accordingly, to the extent oxygen and hydrogen are present within the second volume **106b**, the electrochemical stack **200** manages these streams separately and directs these streams to different portions (i.e., isolated volumes) of the cabinet **104** to reduce the likelihood of inadvertent mixing of oxygen and hydrogen to form a combustible mixture, as compared to a configuration in which oxygen and hydrogen are processed within the same, enclosed volume.

(26) In general, the water circuit **114** may optionally include a reservoir (e.g., water tank) **118** in fluid communication between a separator **120** and a pump **122** via respective fluid conduits. In certain implementations, the reservoir **118** may be coupled to an external water source (e.g., water pipe, not shown) to receive a supply of water suitable for meeting the demands of the electrochemical stack **200**. The connection between the reservoir **118** and the external water source may be made outside of the cabinet **104** to facilitate connection of the system **100** to an industrial water supply and, in some instances, to reduce the likelihood of damaging equipment in one or more of the first volume **106a**, the second volume **106b**, or the third volume **106c** in the event of a leak in the connection between the external water source and the reservoir **118**. It shall be appreciated that the water circuit **114** may include any of various different types of equipment useful for managing properties of the water flowing through the system **100**. As an example, the water circuit **114** may include filtration or other processing equipment useful for purification of process water to reduce the concentration of contaminants that may degrade performance of other components (e.g., the electrochemical stack **200**) over time. Additionally, or alternatively, the water circuit **114** may include a heat exchanger (not shown) in thermal communication with one or more of the reservoir **118**, the separator **120**, or the pump **122** to manage the temperature of each component and/or manage the temperature of water flowing through each component.

(27) The pump **122** may be in fluid communication with the electrochemical stack **200** via a feed conduit **124** extending from the pump **122** in the first volume **106a** to the first fluid connector **110a** of the electrochemical module **102**. The feed conduit **124** may extend through the wall **105a** between the first volume **106a** and the second volume **106b**. In use, the pump **122** may be powered to move purified water from the reservoir **118**, along the feed conduit **124** extending from the first volume **106a** to the second volume **106b**, and into the electrochemical stack **200** in the second volume **106b**. Thus, the pump **122** may be operable to deliver purified water to the second volume **106b** while being partitioned from equipment in each of the second volume **106b** and the third volume **106c**. Such partitioning of the pump **122** may be advantageous for, among other things, reducing the likelihood that heat generated by the pump **122** during operation may serve as an ignition source for a hydrogen-containing mixture. For example, in the event of a hydrogen leak in the second volume **106b** and/or the third volume **106c**, an ignitable hydrogen-air mixture may inadvertently form in the second volume **106b** and/or the third volume **106c**. Continuing with this example, keeping the pump **122** partitioned away from the second volume **106b** and the third volume **106c** may, therefore, reduce the likelihood that ignition can occur before the ignitable hydrogen-air mixture can be detected and the system safely shut down.

(28) In some implementations, the water circuit **114** may include a recirculation circuit **126** in fluid communication between the first fluid connector **110b** and the separator **120**. Through the fluid communication with the first fluid connector **110b**, the recirculation circuit **126** may receive an exit flow consisting essentially of water and oxygen from the anode portion of the electrochemical stack **200**. At least a portion of the recirculation circuit **126** may extend from the second volume **106b** to the first volume **106a** through the wall **105b** to direct the flow of water and oxygen from the

electrochemical stack **200** in the second volume **106b** to the separator **120** in the first volume **106a**. By carrying oxygen to the separator **120** in the first volume **106a** partitioned from the second volume **106b**, the recirculation circuit **126** may reduce the likelihood that oxygen in the excess water flowing from the electrochemical module **102** may inadvertently escape into the second volume **106b** and/or the third volume **106c** to form an ignitable mixture with hydrogen.

(29) The separator **120** may be any one or more of various different types of gas-liquid separators suitable for separating oxygen from excess water in the return flow moving through the recirculation circuit **126** from the electrochemical module **102**. For example, the separator **120** may comprise a dryer, a condenser or another device which separates oxygen from excess water through gravity, with the excess water settling along a bottom portion of the separator **120** and oxygen collecting along a top portion of the separator **120**. More generally, the separator **120** may operate to separate oxygen from excess water without the use of power or moving parts that could otherwise act as potential ignition sources in the system **100**. The oxygen collected by the separator **120** may be directed out of the first volume **106a** to be vented to an environment outside of the cabinet **104** or to be used as a process gas for another part of a plant. By way of example and not limitation, the oxygen collected by the separator **120** may be removed from the separator **120** using a suction pump or blower. The excess water collected by the separator **120** may be directed to the reservoir **118** to be circulated through the electrochemical stack **200** again. That is, more generally, the separator **120** may remove oxygen from the cabinet **104** at a position away from hydrogen-related equipment in the second volume **106b** and the third volume **106c** while facilitating efficient use of water in the formation of hydrogen.

(30) In general, the hydrogen circuit **116** may collect a hydrogen-containing product stream formed by the electrochemical stack **200** in the second volume **106b** and process this product stream using equipment partitioned from the first volume **106a** and the second volume **106b**. In this context, processing the product stream may include removing moisture from the product stream to produce substantially pure hydrogen. That is, removing moisture from hydrogen may reduce the potential for moisture to interfere with one or more downstream processes, with such interference potentially including degradation of downstream equipment. Further, or instead, given considerations associated with safety and energy-to-hydrogen efficiency of the system **100**, processing the product stream in the hydrogen circuit **116** may require little or no energy while recovering all or substantially all (e.g., greater than about 99 percent) of the hydrogen produced by the electrochemical stack **200**.

(31) In some implementations, the hydrogen circuit **116** may include a product conduit **128** and a dryer **130** in fluid communication with one another. More specifically, the product conduit **128** may extend through the wall **105b** between the second volume **106b** and the third volume **106c**. The product conduit **128** may be in fluid communication between inlet portion **132** of the dryer **130** and the second fluid connector **112** of the electrochemical module **102**. Thus, in use, a product stream consisting essentially of hydrogen and water (e.g., water vapor) may move from the anode side of the electrochemical stack **200** to the inlet portion **132** of the dryer **130** via the second fluid connector **112** and the product conduit **128**. As compared to the mixture of oxygen and excess water in the exit flow from the anode portion of the electrochemical stack **200** into the recirculation circuit **126**, the product stream may be at a higher pressure. To reduce the likelihood of hydrogen leaking into the third volume **106c**, the connections between the product conduit **128** and each of the second fluid connector **112** and the dryer **130** may include gas tight seals.

(32) The dryer **130** may be, for example, pressure swing adsorption (PSA), a temperature swing adsorption (TSA) system or a hybrid PSA-TSA system. The dryer **130** may include one or more beds of a water-adsorbent material, such as activated carbon, silica, zeolite or alumina. As the product mixture consisting essentially of hydrogen and water moves through from the inlet portion **132** to an outlet portion **134** of the dryer **130**, at least a portion of the water may be removed from the product mixture through adsorption of either water or hydrogen in the bed of water-adsorbent

material. If hydrogen is adsorbed, then it is removed into the outlet conduit **138** during a pressure and/or temperature swing cycle. If water is adsorbed, then it is removed into a pump conduit **140** during the pressure and/or temperature swing cycle. In some instances, adsorption carried out by the dryer **130** may be passive, without the addition of heat or electricity that could otherwise act as ignition sources of an ignitable hydrogen-containing mixture. In such instances, however, considerations related to backpressure created by the dryer **130** in fluid communication with the electrochemical stack **200** may limit the size and, therefore, the single-pass effectiveness of the dryer **130** in removing moisture from the product stream.

(33) At least in view of such considerations related to single-pass effectiveness of the dryer **130**, the hydrogen circuit **116** may further, or instead, include a hydrogen pump **136** in fluid communication between the outlet portion **134** and the inlet portion **132** of the dryer **130** to recirculate the product mixture of hydrogen and water for additional passes through the dryer **130**. For example, the dryer **130** may direct dried hydrogen from the outlet portion **134** of the dryer **130** to an outlet conduit **138** that directs the dried hydrogen to a downstream process or storage in an environment outside of the cabinet **104**. Further, or instead, the dryer **130** may direct a portion of the product stream that has not adequately dried from the outlet portion **134** of the dryer **130** to a pump conduit **140** in fluid communication with the hydrogen pump **136**. In certain instances, at least a portion of the water in the product mixture moving along the pump conduit **140** may condense out of the product mixture and collect in a moisture trap **142** in fluid communication with the pump conduit **140**, before reaching the hydrogen pump **136**. Such moisture condensed in the moisture trap **142** may be collected and/or directed to an environment outside of the cabinet **104**.

(34) The hydrogen pump **136** may be, for example, an electrochemical pump. As used in this context, an electrochemical pump shall be understood to include a proton exchange membrane (i.e., a PEM electrolyte) disposed between an anode and a cathode. The hydrogen pump **136** may generate protons moveable from the anode through the proton exchange membrane to the cathode form pressurized hydrogen. Thus, such an electrochemical pump may be particularly useful for recirculating hydrogen within the hydrogen circuit **116** at least because the electrochemical pumping provided by the electrochemical pump separates hydrogen from water in the mixture delivered to the hydrogen pump **136** via the pump conduit **140** while also pressurizing the separated hydrogen to facilitate moving the pressurized hydrogen to the inlet portion **132** of the dryer **130**.

(35) Alternatively, the hydrogen pump **136** may comprise another hydrogen pumping and/or separation device, such as a diaphragm compressor or blower or a metal-hydride separator (e.g., which selectively adsorbs hydrogen), which may be used in combination with or instead of the electrochemical hydrogen pump. In one embodiment, a plurality of stages of hydrogen pumping and/or re-pressurization may be used. Each stage may comprise one or more of the diaphragm compressor or blower, the electrochemical pump or the metal-hydride separator. In one implementation, the stages may be in a cascade (i.e., series) configuration and/or may be located in separate enclosures.

(36) In certain implementations, the hydrogen pump **136** may be in fluid communication with the moisture trap **142**, where the water separated from hydrogen in the hydrogen pump **136** may be collected and/or directed to an environment outside of the cabinet **104**. Additionally, or alternatively, the pressurized hydrogen formed by the hydrogen pump **136** may be directed along a recovery circuit **144** in fluid communication between the hydrogen pump **136** and the inlet portion **132** of the dryer **130** (e.g., via mixing with the product stream in the product conduit **128**) to recirculate the pressurized hydrogen to the dryer **130**. Among other advantages, recirculating the pressurized hydrogen through the dryer **130** in this way facilitates moving hydrogen out of the cabinet **104** through only a single conduit (e.g., the outlet conduit **138**), which may reduce potential failure modes as compared to the use of multiple exit points.

(37) In some implementations, the separate ventilation and/or forced convection within each of the

first volume **106a**, the second volume **106b**, and the third volume **106c** may be useful for reducing the likelihood of forming an ignitable hydrogen-containing mixture in the respective volume. Further, or instead, forced convection may facilitate controlling temperature in the enclosed environments of the first volume **106a**, the second volume **106b**, and the third volume **106c**. Such temperature control may be useful, for example, for reducing the likelihood that equipment in each respective volume may become an ignition source and/or may fail prematurely.

(38) Accordingly, the system **100** may include a plurality of gas movers **146a,b,c** (referred to collectively as the plurality of gas movers **146a,b,c** and individually as the gas mover **146a**, the gas mover **146b**, and the gas mover **146c**). The plurality of gas movers **146a,b,c** may include any one or more of various different types of fans (e.g., purge fans), blowers, or compressors, unless otherwise specified or made clear from the context. In certain implementations, a powered circuit to each one of the plurality of gas movers **146a,b,c** may be rated for Class 1 Division 2 operation, as specified according to the National Fire Protection Association (NFPA) 70®, National Electric Code® (NEC), Articles 500-503, 2020, the entire contents of which are incorporated herein by reference. In such implementations, each one of the plurality of gas movers **146a,b,c** may be disposed within the cabinet **104**. Alternatively, each one of the plurality of gas movers **146a,b,c** may be mounted externally to the cabinet **104** (e.g., to the roof or sidewall of the cabinet) to reduce the potential for heat or sparks to act as an inadvertent ignition source for contents of the first volume **106a**, the second volume **106b**, or the third volume **106c**.

(39) In general, the gas mover **146a** may be in fluid communication with the first volume **106a**, the gas mover **146b** may be in fluid communication with the second volume **106b**, and the gas mover **146c** may be in fluid communication with the third volume **106c**. For example, each one of the plurality of gas movers **146a,b,c** may be in fluid communication between an environment outside of the cabinet **104** and a corresponding one of the first volume **106a**, the second volume **106b**, and the third volume **106c**, and may be configured to separately ventilate the respective volume of the cabinet **104**. Additionally, or alternatively, each one of the plurality of gas movers **146a,b,c** may be operable to form negative pressure in a corresponding one of the first volume **106a**, the second volume **106b**, and the third volume **106c**, relative to the environment outside of the cabinet **104**. Such negative pressure may be useful, for example, for drawing air from the environment into the first volume **106a**, the second volume **106b**, and the third volume **106c** to reduce the likelihood that any hydrogen leaking into the first volume **106a**, the second volume **106b**, or the third volume **106c** may accumulate in a concentration above the lower ignition limit of a hydrogen-air mixture at the temperature and pressure associated with the cabinet **104**. Further, or instead, negative pressure in the first volume **106a**, the second volume **106b**, and the third volume **106c** may reduce the likelihood that an ignitable, hydrogen containing mixture may escape from the cabinet **104**. In certain instances, the cabinet **104** may be insulated to facilitate maintaining one or more components in the first volume **106a**, the second volume **106b**, and the third volume **106c** within a temperature range (e.g., between about 60° C. and about 80° C.) suitable for operation of the electrochemical stack **200**.

(40) While the plurality of gas movers **146a,b,c** may be useful for reducing the likelihood of unsafe conditions forming in the first volume **106a**, the second volume **106b**, or the third volume **106c**, it shall be appreciated that one or more of these volumes may additionally, or alternatively, include area classified components. In such instances, the corresponding volume may be unventilated.

(41) In certain implementations, the system **100** may include a controller **148** in electrical communication at least with one or more components in the first volume **106a**, the second volume **106b**, or the third volume **106c**. In general, the controller **148** may include one or more processors and a non-transitory computer-readable storage medium having stored thereon instructions for causing the one or more processors to control one or more of startup, operation, or shutdown of any one or more of various aspects of the system **100** to facilitate safe and efficient operation. For example, the controller **148** may include one or more embedded controllers for one or more

components in the first volume **106a**, the second volume **106b**, or the third volume **106c**. Additionally, or alternatively, the controller **148** may be in electrical communication at least with the electrochemical stack **200** and a power source **150**. Continuing with this example, the controller **148** may interrupt power to the electrochemical stack **200** in the event that an anomalous condition is detected. Further, or instead, the controller **148** may provide power to the electrochemical stack **200** after a startup protocol (e.g., purging the first volume **106a**, the second volume **106b**, and or the third volume **106c**) to reduce the likelihood of igniting a hydrogen-containing mixture in the cabinet **104**.

(42) In some implementations, the cabinet **104** may define a fourth volume **106d**, and the controller **148** may be disposed in the fourth volume **106d** while being in wireless or wired communication with one or more of the various different components described herein as being disposed in one or more of the first volume **106a**, the second volume **106b**, or the third volume **106c**. The fourth volume **106d** may be generally located in the vicinity of the first volume **106a**, the second volume **106b**, and the third volume **106c** to facilitate making and/or breaking electrical connections as part of one or more of installation, startup, regular operation, maintenance, or repair. Thus, for example, the fourth volume **106d** may be disposed along a top portion of the cabinet **104** and/or along a back portion of the cabinet **104**, with both locations providing useful access to each of the first volume **106a**, the second volume **106b**, and the third volume **106c** while being away from the first door **152a**, the second door **152b**, and the third door **152c** that may be used to provide access to the first volume **106a**, the second volume **106b**, and the third volume **106c**, respectively. Further, or instead, with the controller **148** disposed therein, the fourth volume **106d** may be fluidically isolated from each of the first volume **106a**, the second volume **106b**, and/or the third volume **106c** by a roof **105c** or back wall of the cabinet **104** to reduce the likelihood of exposing the controller **148** to one or more process fluids during installation, startup, regular operation, shutdown, maintenance, or repair that may compromise operation of the controller **148**.

(43) While the first volume **106a**, the second volume **106b**, and the third volume **106c** have been described as having a negative pressure provided by the plurality of gas movers **146a**, **146b**, and **146c**, the fourth volume **106d** may be in fluid communication with a fan **154** operable to generate positive pressure in the fourth volume **106d**, relative to an environment outside of the fourth volume **106d**, to control temperature of the controller **148** and/or other components within the fourth volume **106d**. Further, or instead, while the fourth volume **106d** has been described as housing the controller **148**, it shall be appreciated that the fourth volume **106d** may house all controls and power electronics for the system **100**, as may be useful for reducing the likelihood that inadvertent sparking or overheating of one or more of such components can ignite a hydrogen-containing mixture in one or more of the first volume **106a**, the second volume **106b**, or the third volume **106c**.

(44) In certain implementations, the controller **148** may further, or instead, monitor one or more ambient conditions in the first volume **106a**, the second volume **106b**, and the third volume **106c** to facilitate taking one or more remedial actions before an anomalous condition results in damage to the system **100** and/or to an area near the system **100**. In particular, given the potential damage that may be caused by the presence of an ignitable hydrogen-containing mixture within the cabinet **104**, the system **100** may include a plurality of gas sensors **158a,b,c** (referred to collectively as the plurality of gas sensors **158a,b,c** and individually as the gas sensor **158a**, the gas sensor **158b**, and the gas sensor **158c**). Each one of the plurality of gas sensors **158a,b,c** may include any one or more of various different types of hydrogen sensors, such as one or more of optical fiber sensors, electrochemical hydrogen sensors, thin film sensors, and the like. To facilitate robust detection of hydrogen within the cabinet **104**, the gas sensor **158a** may be disposed in the first volume **106a**, the gas sensor **158b** may be disposed in the second volume **106b**, and the gas sensor **158c** may be disposed in the third volume **106c**. Each one of the plurality of gas sensors **158a,b,c** may be calibrated to detect hydrogen concentration levels below the ignition limit of hydrogen to facilitate

taking remedial action before an ignition event can occur. Toward this end, the controller **148** may be in electrical communication with each one of the plurality of gas sensors **158a,b,c**, and the non-transitory computer readable storage media of the controller **148** may have stored thereon instructions for causing one or more processors of the controller **148** to interrupt electrical communication between the power source **150** and equipment in the cabinet **104** based on a signal, received from one or more of the plurality of gas sensors **158a,b,c**, and indicative of a dangerous hydrogen concentration. Additionally, or alternatively, the signal received from the one or more of the plurality of gas sensors **158a,b,c** may be indicative of a rapid increase in hydrogen concentration.

(45) While the controller **148** may be useful for taking remedial action with respect to potentially hazardous conditions in the cabinet **104**, the system **100** may additionally, or alternatively, include one or more safety features useful for mitigating damage to the system **100** and/or in the vicinity of the system in the event of an explosion. For example, the system **100** may include a pressure relief valve **160** in fluid communication with at least the third volume **106c** of the cabinet **104**. The pressure relief valve **160** may be a mechanical valve that is self-opening at a predetermined threshold pressure in the third volume **106c**. In some instances, the predetermined threshold pressure may be a pressure increase resulting from leakage of pressurized hydrogen into the third volume **106c**. Alternatively, the predetermined threshold pressure may be a high pressure associated with a rapid pressure rise associated with combustion of a hydrogen-containing mixtures. In each case, the pressure relief valve **160** may vent contents of the third volume **106c** to the environment to mitigate damage that may otherwise occur.

(46) In general, the components within the cabinet **104** may be connectable to external resources from a location outside of the cabinet **104**, such as along one or more surfaces of the cabinet **104**. Without the need for personnel to open the cabinet **104**, such connections may facilitate installation of the system **100**. Further, or instead, for an otherwise comparable arrangement of components, connections made on the outside of the cabinet **104** may provide additional spacing between components in each of the first volume **106a**, the second volume **106b**, and the third volume **106c**. This, in turn, may be useful for providing trained personnel with better access to components within the cabinet **104**. Further, or instead, connecting components along one or more outer surfaces of the cabinet **104** may provide advantages with respect to safety. For example, electrical contacts **156** may be disposed on an outer surface of the cabinet **104** (e.g., along an outer surface of the cabinet **104** defining the fourth volume **106d**), and the electrical contacts **156** may be in electrical communication with at least the electrochemical stack **200** via the controller **148**. Continuing with this example, the electrical contacts **156** may be releasably engageable (e.g., via a contactor or fuse) in electrical communication with the power source **150** located on the outside of the cabinet **104**. In the event that a disconnect function causes a spark, the spark is located outside of the cabinet **104** and generally away from potentially ignitable hydrogen-containing gas mixtures that may inadvertently form in the first volume **106a**, the second volume **106b**, and/or the third volume **106c**.

(47) Having described certain aspects of the overall layout of the system **100** useful for safely producing hydrogen within a small footprint, attention is now directed to specific features of the electrochemical module **102** itself that may facilitate separately managing water and gas in the electrochemical module **102** to provide additional, or alternative, safety during operation of the system **100** and/or to facilitate installation, maintenance, and/or repair of the system **100**, thus reducing downtime associated with such events.

(48) Referring now to FIG. 2A-2C, the electrochemical stack **200** may include a first membrane electrode assembly (MEA) **201**, a second membrane electrode assembly (MEA) **202**, and a bipolar plate **204** that collectively define two complete electrochemical cells for the generation of hydrogen. The electrochemical stack **200** may also include a first end plate **206** and a second end plate **208** that may sandwich the first MEA **201**, the second MEA **202**, and the bipolar plate **204**

into contact with one another and direct the flow of fluids into and out of the electrochemical stack **200**. While the electrochemical stack **200** is described as including two complete cells—a single bipolar plate and two MEAs—it shall be appreciated that this is for the sake of clarity of explanation and illustration only. It shall be more generally understood that the electrochemical stack **200** may include any number of MEAs and bipolar plates useful for meeting the hydrogen generation demands of the system **100** shown in FIGS. **1A** and **1B**, while maintaining separation between pressurized hydrogen and lower pressure water and oxygen flowing through the electrochemical stack **200**. That is, unless otherwise specified or made clear from the context, the electrochemical stack **200** may include more than one bipolar plate, a single MEA, and/or more than two MEAs. Further, or instead, while the electrochemical stack **200** is shown as including the first end plate **206** in contact with the first MEA **201** and the second end plate **208** in contact with the second MEA **202**, it shall be appreciated that this is again for the sake of clear and efficient description. That is, in some instances, an instance of the bipolar plate **204** may be disposed between the first end plate **206** and the first MEA **201** and/or between the second end plate **208** and the second MEA **202**, without departing from the scope of the present disclosure.

(49) In general, the first MEA **201** and the second MEA **202** may be identical to one another. For example, the first MEA **201** may include an anode **210a**, a cathode **212a**, and a proton exchange membrane (e.g., a PEM electrolyte) **214a** therebetween. Similarly, the second MEA **202** may include an anode **210b**, a cathode **212b**, and a proton exchange membrane **214b** therebetween. The anodes **210a**, **210b** may each comprise an anode catalyst (i.e., electrode) contacting the membrane and an optional anode fluid diffusion layer. The cathodes **212a**, **212b** may each comprise a cathode catalyst (i.e., electrode) contacting the membrane and an optional cathode gas diffusion layer. The anode electrode may comprise any suitable anode catalyst, such as an iridium layer. The anode fluid diffusion layer **246** may comprise a porous material, mesh or weave, such as a porous titanium sheet or a porous carbon sheet. The cathode electrode may comprise any suitable cathode catalyst, such as a platinum layer. The cathode gas diffusion layer may comprise porous carbon. Other noble metal catalyst layers may also be used for the anode and/or cathode electrodes. The electrolyte may comprise any suitable proton exchange (e.g., hydrogen ion transport) polymer membrane, such as a Nafion® membrane composed of sulfonated tetrafluoroethylene based fluoropolymer-copolymer having a formula $C_{0.7}HF_{1.3}O_{0.5}S_{0.2}F_{0.4}$.

(50) The bipolar plate **204** may be disposed between the cathode **212a** of the first MEA **201** and the anode **210b** of the second MEA **202**. In general, the bipolar plate **204** may include a substrate **222**, an anode gasket **224**, and a cathode gasket **226**. The substrate **222** has an anode (i.e., water) side **228** and a cathode (i.e., hydrogen) side **230** opposite one another. The anode gasket **224** may be fixed to the anode side **228** of the substrate **222**, and the cathode gasket **226** may be fixed to the cathode side **230** of the substrate **222**. Such fixed positioning of the anode gasket **224** and the cathode gasket **226** on opposite sides of the substrate **222** may facilitate forming two seals that are consistently placed relative to one another and relative to the first MEA **201** and the second MEA **202** on either side of the bipolar plate **204**. The gaskets form a double seal around the active areas (i.e., anode (e.g., water) flow field **234** and cathode (e.g., hydrogen) flow field **240**) located on respective opposite sides **228**, **230** of the bipolar plate **204**. Further, or instead, in instances in which an electrochemical stack includes an instance of an MEA between two instances of the bipolar plate **204**, the anode gasket **224** and the cathode gasket **226** may form a double seal along an active area of the MEA. Thus, more generally, it shall be appreciated that the anode gasket **224** and the cathode gasket **226** may form a sealing engagement with one or more MEAs in an electrochemical stack to isolate flows within the electrode stack and, thus, reduce the likelihood that pressurized hydrogen may inadvertently mix with a flow of water and oxygen exiting the electrochemical stack to create a combustible hydrogen-oxygen mixture in the system **100** shown in FIGS. **1A** and **1B**.

(51) The substrate **222** may be formed of any one or more of various different types of materials

that are electrically conductive, thermally conductive, and have strength suitable for withstanding the high pressure of hydrogen flowing along the cathode side **230** of the substrate **222** during use. Thus, for example, the substrate **222** may be at least partially formed of one or more of plasticized graphite or carbon composite. Further, or instead, the substrate **222** may be advantageously formed of one or more materials suitable for withstanding prolonged exposure to water on the anode side **228** of the substrate **222**. Accordingly, in some instances, the anode side **228** of the substrate **222** may include an oxidation inhibitor coating that is electrically conductive, examples of which include titanium, titanium oxide, titanium nitride, or a combination thereof. The oxidation inhibitor may generally extend at least along those portions of the anode side **228** of the substrate **222** exposed to water during operation of the electrochemical stack **200**. That is, the oxidation inhibitor may extend at least along the anode flow field **234** inside the anode gasket **224** on the anode side **228** of the substrate **222**. In some implementations, the oxide inhibitor may extend along the plurality of anode ports (i.e., water riser openings) **232** which extend from the anode side **228** to the cathode side **230** of the substrate **222**. The oxidation inhibitor may also be located in the anode plenums **235** which connect the anode portions **232** to the anode flow field **234** on the anode side of the substrate **222**.

(52) A cathode ring seal **237** may be located around each cathode port (i.e., hydrogen riser opening) **238** on the anode side **228** of the substrate, as shown in FIG. 2B. The cathode ring seal **237** prevent hydrogen from leaking out into the anode flow field **234** on the anode side **228** of the substrate **222**. In contrast, an anode ring seal **233** may be located around each one or more anode ports **232** on the cathode side **230** of the substrate **222**. For example, as shown in FIG. 2C, two anode ports **232** are surrounded by a common anode ring seal **233** to prevent water from flowing into the cathode flow field **240** on the cathode side of the substrate **222**.

(53) The anode flow field **234** includes a plurality of straight and/or curved ribs **235** separated by flow channels **236** oriented to direct a liquid (e.g., purified water) between at least some of the plurality of anode ports **232**, such as may be useful for evenly distributing purified water along the anode **210b** of the second MEA **202** in the configuration shown in FIG. 2A. The anode gasket **224** may circumscribe the anode flow field **234** and the plurality of anode ports **232** along the anode side **228** of the substrate **222** to limit the movement of purified water moving along the anode **210b**. That is, the anode side **228** of the substrate **222** may be in sealed engagement with the anode **210b** of the second MEA **202**, via the anode gasket **224**, such that anode channels **236** are located therebetween. Under pressure provided by a source external to the electrochemical stack **200** (e.g., such as the pump **122** of the water circuit **114** shown in FIG. 1B), a liquid provided from the first fluid connector **110a** flows along the anode channels **236** is directed across the anode **210b** of the second MEA **202**, from one instance of the plurality of anode ports **232** to another instance of the plurality of anode ports **232**, where the liquid (e.g., remaining water and oxygen) may be directed out of the electrochemical stack **200** through another first fluid connector **110b**.

(54) Additionally the substrate **222** may include plurality of cathode ports (i.e., hydrogen riser openings) **238**, each extending from the anode side **228** to the cathode side **230** of the substrate **222**. The cathode side **230** of the substrate **222** may include cathode flow field **240**. The cathode flow field **240** includes a plurality of straight and/or curved ribs **241** separated by cathode flow channels **242** oriented to direct gas (e.g., hydrogen) toward the plurality of cathode ports **238**, such as may be useful for directing pressurized hydrogen formed along the cathode **212a** of the first MEA **201** in the configuration shown in FIG. 2A. Cathode plenums **239** may be located between the respective cathode ports **238** and the cathode flow field **240**. The cathode gasket **226** may circumscribe the cathode flow field **240**, the cathode plenums **239** and the plurality of cathode ports **238** along the cathode side **230** of the substrate **222** to limit movement of the pressurized hydrogen along the cathode **212a**. For example, the cathode side **230** of the substrate **222** may be in sealed engagement with the cathode **212a** of the first MEA **201**, via the cathode gasket **226**, such that the cathode flow channels **242** are defined between the cathode **212a** of the first MEA **201** and the

cathode side **230** of the substrate **222**. The pressure of the hydrogen formed along the cathode **212a** may move the hydrogen along at least a portion of the cathode channels **242** and toward the cathode ports **238** located diagonally opposite to the cathode inlet port. The pressurized hydrogen may flow out of the cathode ports **238** and out of the electrochemical stack **200** through the second fluid connector **112** to be processed by the hydrogen circuit **116** as shown in FIG. **1B**.

(55) The anode gasket **224** on the anode side **228** of the substrate **222** and the cathode gasket **226** on the cathode side **230** of the substrate **222** may have different shapes (as shown in FIGS. **2B** and **2C**). For example, the anode gasket **224** may extend between the plurality of anode ports **232** and the plurality of cathode ports **238** on the anode side **228** of the substrate **222**. In other words the anode gasket **224** surrounds the anode ports **232** and the anode flow field **234** on one lateral side, but leaves the cathode portions **238** outside its circumscribed area. In an installed position, therefore, the anode gasket **224** may fluidically isolate anode flow from cathode flow.

(56) In contrast, the cathode gasket **226** on the cathode side **230** of the substrate **222** does not extend between the plurality of anode ports **232** and the plurality of cathode ports **238**. In other words the cathode gasket **226** surrounds the anode ports **232**, the cathode portions **238** and the cathode flow field **240**. Instead, the anode ring seals **233** isolate the anode portions **232** from the cathode ports **238** and the cathode flow field **240** on the cathode side **230** of the substrate **222**.

(57) In one configuration the anode flow field **234** and the cathode flow field **240** may have the same shape, albeit on opposite side of the substrate **222** to provide the same active area along the first MEA **201** and the second MEA **202**. Thus, taken together, it shall be appreciated that the differences in shape between the anode gasket **224** and the cathode gasket **226** along with positioning of the anode ring seals and the same shape of the anode flow field **234** and the cathode flow field **240** may result in different sealed areas. These different sealed areas are complementary to one another to facilitate fluidically isolating the lower pressure flow of purified water along the anode channels **236** from the pressurized hydrogen flowing along the cathode channels **242** while nevertheless allowing each flow to move through the electrochemical stack **200** and ultimately exit the electrochemical stack **200** along different channels.

(58) In certain implementations, the cathode flow field **240** may be shaped such that a minimum bounding rectangle of the cathode flow field **240** is square. As used in this context, the term minimum bounding rectangle shall be understood to be a minimum rectangle defined by the maximum x- and y-dimensions of the cathode flow field **240**. The plurality of cathode ports **238** may include two cathode ports per substrate **222** which are located in diagonally opposite corners from one another with respect to the minimum bounding rectangle (e.g., within the minimum bounding rectangle). The other two diagonally opposite corners lack the cathode ports **238**. In instances in which the minimum bounding rectangle is square, the diagonal positioning of the cathode ports **238** relative to the minimum bounding rectangle may facilitate flow of pressurized hydrogen diagonally along the entire cathode flow field **240**, while leaving a large margin of the substrate **222** material for strengths against the contained internal hydrogen pressure. Alternatively, the substrate **222** may be a rectangle. The plurality of cathode ports **238** are positioned away from edges of the substrate **222** such that each one of the plurality of cathode ports **238** is well-reinforced by the material of the substrate **222** between the respective one of the plurality of cathode ports **238** and the closest edge of the substrate **222**.

(59) Given the large pressure differential between the flow of pressurized hydrogen along the cathode channels **242** and the flow of water and oxygen along the anode channels **236**, the electrochemical stack **200** may include the anode fluid diffusion layer disposed in the anode channels **236** and optionally between the anode electrode of the anode **210b** of the second MEA **202** and the anode side **228** (e.g., anode ribs **235**) of the substrate **222**. The porous material of the anode fluid diffusion layer **246** may generally permit the flow of water and oxygen through the anode channels **236** without a substantial increase in flow restriction through the anode channels **236** while providing structural support on the anode side **228** of the substrate **222** to resist collapse

that may result from the pressure difference on opposite sides of the substrate **222**. For the sake of clear illustration, the porous material **246** is shown along only one anode channel **236**. It shall be understood, however, that porous material **246** may be disposed inside all of the anode channels **236** in certain implementations.

(60) As an additional, or alternative, safety measure, the electrochemical stack **200** may include a housing **248** disposed about the first MEA **201**, the second MEA **202**, the bipolar plate **204**, the first end plate **206**, and the second end plate **208**, as shown in FIG. 2A. More specifically, the housing **248** may be formed of one or more materials useful for absorbing force of one or more materials that may become ejected in the event of a failure event (e.g., failure under the force of pressurized hydrogen and/or failure resulting from explosion of an inadvertent hydrogen-containing mixture). As an example, the housing **248** may include one or more of metal or aramid (e.g., Kevlar®) fibers.

(61) Having described various features of the electrochemical stack **200**, attention is now directed to a description of operation of the electrochemical stack **200** to form pressurized hydrogen with water and electricity as inputs. In particular, as shown in FIG. 2A, an electric field E (i.e., voltage) may be applied across the electrochemical stack **200** (i.e., between the end plates **206** and **208**) from the power source **150** shown in FIG. 1B. The bipolar plate **204** may electrically connect the first MEA **201** and the second MEA **202** in series with one another such that electrolysis may take place at the first MEA **201** and the second MEA **202** to form a flow of pressurized hydrogen that is maintained fluidically isolated from lower pressure water and oxygen, except for proton exchange occurring through the proton exchange membrane **214a** and the proton exchange membrane **214b**.

(62) Purified water (e.g., from the water circuit **114** shown in FIG. 1B) may be introduced into the electrochemical stack **200** via the first fluid connector **110a** of the electrochemical module **102** as shown in FIG. 1B. Within the electrochemical stack **200**, the purified water may flow along an intake channel **216** that extends through the bipolar plate **204**, among other components, to direct the purified water to the anode **210a** of the first MEA **201** and to the anode **210b** of the second MEA **202**. With the electric field E applied across the anode **210a** and the cathode **212a** of the first MEA **201**, the purified water may break down along the anode **210a** into protons ($H_{sup.}^{+}$) and oxygen. The protons ($H_{sup.}^{+}$) may move from the anode **210a** to the cathode **212a** through the proton exchange membrane **214a**. At the cathode **212a**, the protons ($H_{sup.}^{+}$) may combine with one another to form pressurized hydrogen along the cathode **212a**. Through an analogous process, pressurized hydrogen may also be formed along the cathode **212b** of the second MEA **202**. The flows of pressurized hydrogen formed by each of the first MEA **201** and the second MEA **202** may combine with one another and flow out of the electrochemical stack **200** via two hydrogen exhaust channels **218** that extends through the bipolar plate **204**, among other components, to ultimately direct the pressurized hydrogen out of the second fluid connector **112** of the electrochemical module **102** and toward the hydrogen circuit **116** for processing (as shown in FIG. 1B and discussed above). The flows of oxygen and water along the anode **210a** and the anode **210b** may combine with one another and flow out of the electrochemical stack **200** via the outlet anode ports **232** and an outlet channel **220** that extends through the end plate **206**, among other components, to direct this stream of water and oxygen out of the first fluid connector **110b** of the electrochemical module **102** and toward the water circuit **114** for processing (as shown in FIG. 1B and discussed above).

(63) As discussed above, the bipolar plate **204** may be in sealed engagement with the cathode **212a** of the first MEA **201** and the anode **210b** of the second MEA to facilitate keeping pressurized hydrogen formed along the cathode **212a** of the first MEA **201** separate from water and oxygen flowing along the anode **210b** of the second MEA **202**. This separation is useful for reducing the likelihood of leakage of pressurized hydrogen from the electrochemical stack **200** and, thus, may be useful in addition to, or instead of, any one or more aspects of the modularity of the system **100** (shown in FIGS. 1A and 1B) with respect to safely producing industrial-scale quantities of hydrogen through electrolysis. Additionally, or alternatively, as described in greater detail below

with respect to FIGS. 3A and 3B, the sealed engagement facilitated by the bipolar plate **204** may facilitate dismantling the electrochemical module **102** (e.g., to repair, maintain, and/or replace the electrochemical stack **200**) with a lower likelihood of spilling water in the vicinity of the cabinet **104** shown in FIG. 1A.

(64) Referring now to FIGS. 3A and 3B, the electrochemical module **102** may include a liquid-management section **302** and a gas-management section **304** that are releasably securable to one another (e.g., using clamps, bolts, or a combination thereof) along an interface **305** to facilitate installation, maintenance, and/or repair. For example, the gas-management section **304** may be removable from the liquid-management section **302** without the need to break water connections at the first fluid connectors **110a,b**. As compared to installations requiring removal of water connections, the ability to remove the gas-management section **304** from the liquid-management section **302** may reduce the time required performing a mechanical operation related to installation, maintenance, and/or repair. Further, or instead, because water connections may remain intact, inadvertent dispersion of water around the cabinet **104** shown in FIG. 1A is less likely.

(65) In general, the liquid-management section **302** may include the plurality of first fluid connectors **110a,b** fluidly connected to respective inlet and outlet water manifolds **306a,b**. Each one of the plurality of first fluid connectors **110a,b** may be in fluid communication with the respective manifold **306a,b**. In turn, the manifolds **306a,b** may include respective liquid connections **310a**, **310b** (e.g., O-rings and/or tubes) securable to the gas-management section **304**, to deliver purified water to the gas-management section **304** via the first fluid connector **110a** and the liquid connection **310a** and to receive an anode-out flow of water and oxygen via the first fluid connector **110b** and the liquid connection **310b**. The manifolds **306a,b** may comprise hollow plastic or metal boxes. The liquid-management section **302** may include a support, such as legs **308** or a pedestal-type support.

(66) An optional separator plate **309**, such as a stainless steel plate, may be located on the top of the liquid-management section **302**, such that the respective liquid connections **310a**, **310b** extend through the separator plate. For example, the respective liquid connections **310a**, **310b** may comprise holes in the separator plate **309** surrounded by respective O-rings.

(67) Referring now to FIG. 2A and FIGS. 3A and 3B, the gas-management section **304** of the electrochemical module **102** may include the electrochemical stack **200**, a collector plate **312** and the second fluid connector **112**. Thus, stated differently, the liquid-management section **302** and the gas-management section **304** may be separable from one another along low-pressure water connections **110a,b** while high-pressure connections **112** associated with the flow of pressurized hydrogen out of the electrochemical module **102** need not be disturbed and, thus, failure modes associated with repeatedly breaking and reestablishing high-pressure connections are not present in the electrochemical module **102**. The collector plate **312** may be oriented perpendicular to the direction of the connectors **110a,b** and **112** (e.g., out of the page in FIG. 3A).

(68) FIGS. 4A and 4B illustrate exemplary systems of the present disclosure. Referring now to FIG. 4A, the system **400** includes an electrolyzer stack **402** which produces hydrogen from water **420**. The electrolyzer stack may be any electrolyzer stack described herein. The output wet hydrogen **422** is directed to a dryer **406**, which may be any dryer described herein. The dryer removes water from the hydrogen, producing a dry hydrogen stream **426** which is optionally directed to a purifier **408**. The purifier **408** removes additional water and other impurities (e.g., oxygen, nitrogen, hydrocarbons, argon, etc.) from the hydrogen gas and provides a purified hydrogen stream **430** to a hydrogen-using application **410**, which utilizes the purified hydrogen **430**. The hydrogen-using application **410** may be any hydrogen-using device or process, such as a glass float furnace, a metals furnace, or other processes devices requiring hydrogen. The hydrogen-using application **410** may produce exhaust hydrogen **432** which can be directed either to a blending tank **412** to be recycled back into the system **400**, or it can be sent to an output stream **442**. The output stream **442** may direct the exhaust hydrogen to a scrubber, another process that

uses the exhaust hydrogen, or it may be vented to the environment. An oxygen sensor **416** may be provided to determine the oxygen content of the exhaust hydrogen stream **432**. Additionally, the system may optionally further include valves and other instrumentation such that if oxygen or other impurities are detected, the exhaust gas **432** may be directed away from the system **400** and not be recycled. The blending tank **412** is operable to mix the exhaust hydrogen stream **432**, a purge gas stream **428** from the purifier **408**, and purge gas stream **424** from the dryer **406**. The purge gas stream **424** and the purge gas stream **428** may each contain a high concentration of water. This forms a blended stream **434** which is directed to a humidifier, forming a humidified stream **436**. The humidified stream **436** is directed to a hydrogen pump **404**, which produces a purge water stream **438** and a wet hydrogen stream **440**. The hydrogen pump **404** may be any hydrogen pump described herein. The wet hydrogen stream **440** is then recycled into the system **400** by directing it to the dryer **406**. The wet hydrogen stream **440** may be recombined with the wet hydrogen stream **422** before entering the dryer **406** as shown in FIG. 4A, or the wet hydrogen stream **440** may enter the dryer **406** separately.

(69) The power electronics for the hydrogen pump **404** may be common with the power supply for the electrolyzer stack **402** and are fashioned in a modular way for on-stream service. The hydrogen pump **404** may be operated in constant voltage mode such that it scavenges hydrogen gas when it is present. In another embodiment, the hydrogen pump **404** may be operated at a constant stoichiometry mode wherein the input flows to the hydrogen pump **404** are measured or estimated such that current may be set at an appropriate stoichiometry level.

(70) The hydrogen pump stacks may be capable of repressurizing the wet hydrogen stream **440** to the same pressure as the wet hydrogen stream **422**. In one embodiment, a cascade of hydrogen pumps **404** may be used to reduce the fraction of lost hydrogen. Alternatively, a compressor or expander may be included in the system to increase or decrease the pressure of the hydrogen.

(71) The system **400** may further include a heat exchanger to increase or decrease the temperature of the hydrogen. Heat exchangers suitable for use in a system of the present disclosure are well-known to those having ordinary skill in the art. In particular, the heat exchanger may be located downstream from the blending tank **412** and may be operable to increase the temperature of the blended stream **434**. The temperature of the blended stream **434** may be increased to a temperature that is optimal for the functioning of the hydrogen pump. In preferred embodiments, the increased temperature of the blended stream **434** may be from about 60° C. to about 80° C.

(72) Referring now to FIG. 4B, the system **401** includes an electrolyzer stack **402** which produces hydrogen from water **420**. The electrolyzer stack may be any electrolyzer stack described herein. The output wet hydrogen **422** is directed to a dryer **406**, which may be any dryer described herein. The dryer removes water from the hydrogen, producing a dry hydrogen stream **426** which is optionally directed to a purifier **408**. The purifier **408** removes additional water and other impurities from the hydrogen gas and provides a purified hydrogen stream **430** to a hydrogen-using application **410**, which utilizes the purified hydrogen **430**. The hydrogen-using application **410** may be any hydrogen-using device or process, such as a glass float furnace, a metals furnace, or other processes devices requiring hydrogen. The hydrogen-using application **410** may produce exhaust hydrogen **432** which can be directed to a humidifier **414**. The humidified hydrogen stream **436a** may then be directed to a hydrogen pump **404a**, which produces a purge water stream **438a** and a wet hydrogen stream **440**. The purge water stream **438a** is preferably a liquid stream and may contain low levels of hydrogen. Furthermore, a purge gas stream **428** from the purifier **408** is directed to a humidifier **414**. The purge gas stream **428** may contain a high concentration of water. The humidified hydrogen stream **436b** is then directed to a hydrogen pump **404b**, which produces a purge water stream **438b** and a wet hydrogen stream **440**. The purge water stream **438b** is preferably a liquid stream, and may contain low levels of hydrogen. Still further, a purge gas stream **424** from the dryer **406** is directed to one or more hydrogen pumps **404c** and/or one or more humidifiers **414**. The purge gas stream **424** may contain a high concentration of water.

(73) Further provided herein are methods for recovering hydrogen. The methods may be performed using any system of the present disclosure. The method generally comprises providing a wet hydrogen stream from an electrolyzer to an inlet of a dryer, outputting a dry hydrogen stream from a first outlet of the dryer to a hydrogen-using application, providing a purge wet hydrogen stream from a second outlet of the dryer into the inlet of the dryer, and providing an exhaust hydrogen stream from the hydrogen-using application to the inlet of the dryer.

(74) The method may further comprise providing the exhaust hydrogen stream from the hydrogen-using application to the inlet of the dryer by using one or more pumps. The one or more pumps may be any pump described herein; preferably, the pump is an electrochemical hydrogen pump such as a proton exchange membrane disposed between an anode and a cathode.

(75) The method may further comprise humidifying the exhaust hydrogen stream from the hydrogen-using application before providing the exhaust hydrogen stream from the hydrogen-using application to the inlet of the dryer. The humidifying may be accomplished via a humidifier, including any humidifier described herein or known to those having ordinary skill in the art. The method may further comprise humidifying the combined exhaust hydrogen stream from the hydrogen-using application and the purge wet hydrogen stream from the second outlet of the dryer prior to providing the exhaust hydrogen stream from the hydrogen-using application and the purge wet hydrogen stream from the second outlet of the dryer to the inlet of the dryer.

(76) The method may further comprise purifying the dry hydrogen stream from the first outlet of the dryer. The purifying may be accomplished via a purifier, including any purifier described herein or known in the art. The purifying may comprise outputting a purified hydrogen stream from a first outlet of the purifier. The purifying is operable to produce a stream of purified hydrogen from an outlet in the purifier. The purifying may occur before outputting the dry hydrogen stream from the first outlet of the dryer to the hydrogen-using application. The method may further comprise humidifying a purge wet hydrogen stream from an outlet of the purifier by using a humidifier.

(77) The method may further comprise combining the exhaust hydrogen stream from the hydrogen-using application and the purge wet hydrogen stream from the second outlet of the dryer.

Additionally, the method may also further comprise combining the exhaust hydrogen stream from the hydrogen-using application, the purge wet hydrogen stream from the second outlet of the dryer, and a purge wet hydrogen stream from a second outlet of the purifier. The combining may be accomplished by using a blending tank described herein or known to those having ordinary skill in the art.

(78) As used herein, “wet hydrogen” refers to hydrogen that is saturated with water. Those having ordinary skill in the art will appreciate that the amount and/or concentration of water in the wet hydrogen will depend on the temperature and pressure of the wet hydrogen.

(79) As used herein, “dry hydrogen” refers to hydrogen that has a water content of about 10 ppm or less. For example, the dry hydrogen may have a water content of about 10 ppm, about 9 ppm, about 8 ppm, about 7 ppm, about 6 ppm, about 5 ppm, about 4 ppm, about 3 ppm, about 2 ppm, about 1 ppm, or less than about 1 ppm. Preferably, the dry hydrogen has a water content of about 5 ppm or less.

(80) As used herein, “purified hydrogen” refers to hydrogen that is at least about 99.99% pure on a mol percent basis. In some embodiments, the purified hydrogen may be 99.999% pure on a mol percent basis. Similarly, “impure hydrogen” as used herein refers to hydrogen that has not been purified and does not meet the definition of “purified hydrogen” as set forth above.

(81) All documents mentioned herein are hereby incorporated by reference in their entirety. References to items in the singular should be understood to include items in the plural, and vice versa, unless explicitly stated otherwise or clear from the text. Grammatical conjunctions are intended to express any and all disjunctive and conjunctive combinations of conjoined clauses, sentences, words, and the like, unless otherwise stated or clear from the context. Thus, the term “or” should generally be understood to mean “and/or,” and the term “and” should generally be

understood to mean “and/or.”

(82) Recitation of ranges of values herein are not intended to be limiting, referring instead individually to any and all values falling within the range, unless otherwise indicated herein, and each separate value within such a range is incorporated into the specification as if it were individually recited herein. The words “about,” “approximately,” or the like, when accompanying a numerical value, are to be construed as including any deviation as would be appreciated by one of ordinary skill in the art to operate satisfactorily for an intended purpose. Ranges of values and/or numeric values are provided herein as examples only, and do not constitute a limitation on the scope of the described embodiments. The use of any and all examples or exemplary language (“e.g.,” “such as,” or the like) is intended merely to better illuminate the embodiments and does not pose a limitation on the scope of those embodiments. No language in the specification should be construed as indicating any unclaimed element as essential to the practice of the disclosed embodiments.

(83) The above systems, devices, methods, processes, and the like may be realized in hardware, software, or any combination of these suitable for the control, data acquisition, and data processing described herein. This includes realization in one or more microprocessors, microcontrollers, embedded microcontrollers, programmable digital signal processors or other programmable devices or processing circuitry, along with internal and/or external memory. This may also, or instead, include one or more application specific integrated circuits, programmable gate arrays, programmable array logic components, or any other device or devices that may be configured to process electronic signals. It will further be appreciated that a realization of the processes or devices described above may include computer-executable code created using a structured programming language such as C, an object oriented programming language such as C++, or any other high-level or low-level programming language (including assembly languages, hardware description languages, and database programming languages and technologies) that may be stored, compiled or interpreted to run on one of the above devices, as well as heterogeneous combinations of processors, processor architectures, or combinations of different hardware and software. At the same time, processing may be distributed across devices such as the various systems described above, or all of the functionality may be integrated into a dedicated, standalone device. All such permutations and combinations are intended to fall within the scope of the present disclosure.

(84) Embodiments disclosed herein may include computer program products comprising computer-executable code or computer-usable code that, when executing on one or more computing devices, performs any and/or all of the steps of the control systems described above. The code may be stored in a non-transitory fashion in a computer memory, which may be a memory from which the program executes (such as random access memory associated with a processor), or a storage device such as a disk drive, flash memory or any other optical, electromagnetic, magnetic, infrared or other device or combination of devices. In another aspect, any of the control systems described above may be embodied in any suitable transmission or propagation medium carrying computer-executable code and/or any inputs or outputs from same.

(85) The method steps of the implementations described herein are intended to include any suitable method of causing such method steps to be performed, consistent with the patentability of the following claims, unless a different meaning is expressly provided or otherwise clear from the context. So, for example performing the step of X includes any suitable method for causing another party such as a remote user, a remote processing resource (e.g., a server or cloud computer) or a machine to perform the step of X. Similarly, performing steps X, Y and Z may include any method of directing or controlling any combination of such other individuals or resources to perform steps X, Y and Z to obtain the benefit of such steps. Thus, method steps of the implementations described herein are intended to include any suitable method of causing one or more other parties or entities to perform the steps, consistent with the patentability of the following claims, unless a different meaning is expressly provided or otherwise clear from the context. Such parties or entities need not

be under the direction or control of any other party or entity, and need not be located within a particular jurisdiction.

(86) It will be appreciated that the methods and systems described above are set forth by way of example and not of limitation. Numerous variations, additions, omissions, and other modifications will be apparent to one of ordinary skill in the art. In addition, the order or presentation of method steps in the description and drawings above is not intended to require this order of performing the recited steps unless a particular order is expressly required or otherwise clear from the context. Thus, while particular embodiments have been shown and described, it will be apparent to those skilled in the art that various changes and modifications in form and details may be made therein without departing from the scope of the disclosure.

Claims

1. A system for hydrogen recovery comprising: a dryer comprising an inlet that may be fluidly connected to a hydrogen generator comprising an electrolyzer stack, wherein the dryer is a pressure swing adsorption (PSA) dryer, a temperature swing adsorption (TSA) dryer or a hybrid PSA-TSA dryer; a hydrogen-using application comprising an inlet fluidly connected to a dry hydrogen outlet of the dryer and an outlet fluidly connected to the inlet of the dryer, such that a hydrogen exhaust stream from the outlet of the hydrogen-using application is recirculated to the inlet of the dryer.
 2. The system of claim 1, further comprising one or more pumps fluidly connected to the dryer, the hydrogen generator, the hydrogen-using application, or a combination thereof.
 3. The system of claim 2, each of the one or more pumps comprising an inlet fluidly connected to the hydrogen-using application and an outlet fluidly connected to the inlet of the dryer.
 4. The system of claim 2, further comprising one or more humidifiers fluidly connected to the dryer.
 5. The system of claim 4, each of the one or more humidifiers comprising an inlet and an outlet, the outlet fluidly connected to the one or more pumps.
 6. The system of claim 2, further comprising a purifier fluidly connected to the dryer.
 7. The system of claim 6, the purifier comprising an inlet fluidly connected to the dry hydrogen outlet of the dryer and an outlet fluidly connected to the inlet of the hydrogen-using application.
 8. The system of claim 1, further comprising at least one oxygen sensor.
 9. The system of claim 1, the dryer further comprising a wet hydrogen outlet fluidly connected to the inlet of the dryer.
 10. The system of claim 3, the dryer further comprising a wet hydrogen outlet fluidly connected to the inlet of at least one of the one or more pumps.
 11. The system of claim 1, further comprising a blending tank.
 12. The system of claim 11, the blending tank comprising an inlet fluidly connected to the outlet of the hydrogen-using application.
 13. The system of claim 1, further comprising an electrochemical hydrogen pump in fluid communication between the dry hydrogen outlet of the dryer and the inlet of the dryer.
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