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Fuel cell system including fuel exhaust processor and method of operating the same

Abstract

A fuel cell system and method, the system including a hotbox, a fuel cell stack disposed in the hotbox, an anode tail gas oxidizer (ATO) disposed in the hotbox, and a fuel exhaust processor fluidly connected to the hotbox. The fuel exhaust processor includes a first hydrogen pump configured to extract hydrogen from the anode exhaust received from the fuel cell stack and to output the hydrogen to a first hydrogen stream provided to the fuel cell stack, a second hydrogen pump configured to extract hydrogen from anode exhaust output from the first hydrogen pump and to output the hydrogen to the first hydrogen stream, and a third hydrogen pump configured to extract hydrogen from anode exhaust output from the second hydrogen pump and to output the hydrogen to a second hydrogen stream provided to the ATO.

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Background/Summary

CROSS-REFERENCE TO RELATED APPLICATIONS (1) This application is a non-provisional application that claims the benefit of U.S. provisional Application No. 63/278,485, filed on Nov. 12, 2021, the contents of which are herein incorporated by reference in their entirety.

FIELD OF THE INVENTION

(1) Aspects of the present invention relate to fuel cell systems and methods, and more particularly, to fuel cell systems including a fuel exhaust processing module configured to generate purified carbon dioxide and hydrogen streams.

BACKGROUND OF THE INVENTION

(2) Fuel cells, such as solid oxide fuel cells, are electrochemical devices which can convert energy stored in fuels to electrical energy with high efficiencies. High temperature fuel cells include solid oxide and molten carbonate fuel cells. These fuel cells may operate using hydrogen and/or hydrocarbon fuels. There are classes of fuel cells, such as the solid oxide regenerative fuel cells, that also allow reversed operation, such that oxidized fuel can be reduced back to unoxidized fuel using electrical energy as an input.

SUMMARY OF THE INVENTION

(3) According to various embodiments, provided is a fuel cell system comprising: a hotbox; a fuel cell stack disposed in the hotbox; an anode tail gas oxidizer (ATO) disposed in the hotbox; and a fuel exhaust processor fluidly connected to the hotbox and comprising: a first hydrogen pump configured to extract hydrogen from the anode exhaust received from the fuel cell stack and to output the hydrogen to a first hydrogen stream provided to the fuel cell stack; a second hydrogen pump configured to extract hydrogen from anode exhaust output from the first hydrogen pump and to output the hydrogen to the first hydrogen stream; and a third hydrogen pump configured to extract hydrogen from anode exhaust output from the second hydrogen pump and to output the hydrogen to a second hydrogen stream provided to the ATO.

(4) According to various embodiments, provided is a fuel cell system, comprising: a hotbox; a fuel cell stack disposed in the hotbox; an anode tail gas oxidizer (ATO) disposed in the hotbox; and a recycling conduit configured to receive anode exhaust from the fuel cell stack; a splitter fluidly connected to the recycling conduit; a low temperature shift reactor; a hydrogen separator comprising: a first hydrogen pump; a second hydrogen pump that is fluidly connected to the first hydrogen pump; and a third hydrogen pump that is fluidly connected to the second hydrogen pump; a supply conduit that fluidly connects an outlet of the splitter to the hydrogen separator; a first separator conduit fluidly connecting the splitter to the low temperature shift reactor; a second separator conduit fluidly connecting the low temperature shift reactor to the first hydrogen pump; a first return conduit that fluidly connects an outlet of the splitter to the fuel cell stack; a second return conduit that fluidly connects an outlet of the splitter or the separator conduit to the ATO; and a third return conduit that fluidly connects the separator conduit to the second return conduit.

(5) According to various embodiments, provided is a fuel cell system comprising: a hotbox; a fuel cell stack disposed in the hotbox; an anode tail gas oxidizer (ATO) disposed in the hotbox; and a fuel exhaust processor fluidly connected to the hotbox and comprising: a first hydrogen pump configured to extract hydrogen from the anode exhaust received from the fuel cell stack; and a second hydrogen pump configured to extract hydrogen from anode exhaust output from the first

hydrogen pump; wherein the first hydrogen pump and the second hydrogen pump output hydrogen to one or more components of the hotbox.

Description

BRIEF DESCRIPTION OF THE DRAWINGS

(1) The accompanying drawings, which are incorporated herein and constitute part of this specification, illustrate example embodiments of the invention, and together with the general description given above and the detailed description given below, serve to explain the features of the invention.

(2) FIG. 1 is a schematic view of a solid oxide fuel cell (SOFC) system, according to various embodiments of the present disclosure.

(3) FIG. 2 is a schematic view of a fuel exhaust processor that may be included in the SOFC system of FIG. 1, according to various embodiments of the present disclosure.

(4) FIG. 3 is a cross-sectional view of a hydrogen pumping cell that may be included in the fuel exhaust processor of FIG. 2, according to various embodiments of the present disclosure.

(5) FIG. 4A is a perspective view of a shift reactor that may be included in the fuel exhaust processor of FIG. 2, according to various embodiments of the present disclosure, and FIG. 4B is a cross-sectional view of the shift reactor of FIG. 4A.

(6) FIGS. 5-8 are schematic views showing fluid flow through the fuel cell system and fuel exhaust processor of FIGS. 1 and 2, according to various embodiments of the present disclosure.

DETAILED DESCRIPTION OF THE INVENTION

(7) The various embodiments will be described in detail with reference to the accompanying drawings. Wherever possible, the same reference numbers will be used throughout the drawings to refer to the same or like parts. References made to particular examples and implementations are for illustrative purposes, and are not intended to limit the scope of the invention or the claims.

(8) In a solid oxide fuel cell (SOFC) system, a fuel inlet stream may be humidified in order to facilitate fuel reformation reactions such as steam reformation and water-gas shift reactions. In addition, during system startup, shutdown, and power grid interruption events, water may be added to a fuel inlet stream in order to prevent coking of system components such as catalysts.

Conventionally, such humidification is performed by vaporizing water in a steam generator containing corrugated tubing. Water flows through the corrugated tubing and is heated by the cathode recuperator heat exchanger exhaust stream which flows around the outside of the tubing. However, utilizing relatively low-temperature cathode recuperator exhaust stream generally requires substantial lengths of corrugated tubing, in order to absorb enough heat to vaporize the water. Further, the steam generator is relative large and bulky, which also adds to the system size, complexity and manufacturing costs.

(9) In contrast, embodiments of the present disclosure provide a water injector configured to inject water directly into the anode exhaust recycle stream which provides heat to vaporize the water into steam and/or aerosolize the water into droplets small enough to be entrained in the anode exhaust stream. The anode exhaust recycle stream is recycled into the fuel inlet stream provided into the fuel cell stack, such that humidified fuel is provided to the fuel cells of the fuel cell stack. Thus, the prior art steam generator may be omitted to reduce system size, complexity and cost. In addition, the embodiment system may operate using relatively short, non-corrugated water conduit, which may improve system response times and reduce system size and cost.

(10) Sofc Systems

(11) FIG. 1 is a schematic representation of a SOFC system **10**, according to various embodiments of the present disclosure. Referring to FIG. 1, the system **10** includes a hotbox **100** and various components disposed therein or adjacent thereto. The hotbox **100** may contain at least one fuel cell

stack **102**, such as a solid oxide fuel cell stack containing alternating fuel cells and interconnects. One solid oxide fuel cell of the stack contains a ceramic electrolyte, such as yttria stabilized zirconia (YSZ), scandia stabilized zirconia (SSZ), scandia and ceria stabilized zirconia or scandia, yttria and ceria stabilized zirconia, an anode electrode, such as a nickel-YSZ, a nickel-SSZ or nickel-doped ceria cermet, and a cathode electrode, such as lanthanum strontium manganite (LSM). The interconnects may be metal alloy interconnects, such as chromium-iron alloy interconnects. The stacks **102** may be arranged over each other in a plurality of columns.

(12) The hotbox **100** may also contain an anode recuperator heat exchanger **110**, a cathode recuperator heat exchanger **120**, an anode tail gas oxidizer (ATO) **130**, an anode exhaust cooler heat exchanger **140**, a vortex generator **172**, and a water injector **160**. The system **10** may also include a catalytic partial oxidation (CPOx) reactor **200**, a mixer **210**, a CPOx blower **204** (e.g., air blower), a system blower **208** (e.g., main air blower), and an anode recycle blower **212**, which may be disposed outside of the hotbox **100**. However, the present disclosure is not limited to any particular location for each of the components with respect to the hotbox **100**.

(13) The CPOx reactor **200** receives a fuel inlet stream from a fuel inlet **300**, through fuel conduit **300A**. The fuel inlet **300** may be a fuel tank or a utility natural gas line including a valve to control an amount of fuel provided to the CPOx reactor **200**. The CPOx blower **204** may provide air to the CPOx reactor **200** during system start-up. The fuel and/or air may be provided to the mixer **210** by fuel conduit **300B**. Fuel flows from the mixer **210** to the anode recuperator **110** through fuel conduit **300C**. The fuel is heated in the anode recuperator **110** by a portion of the fuel exhaust and the fuel then flows from the anode recuperator **110** to the SOFC stack **102** through fuel conduit **300D**.

(14) The main air blower **208** may be configured to provide an air stream (e.g., air inlet stream) to the anode exhaust cooler **140** through air conduit **302A**. Air flows from the anode exhaust cooler **140** to the cathode recuperator **120** through air conduit **302B**. The air is heated by the ATO exhaust in the cathode recuperator **120**. The air flows from the cathode recuperator **120** to the SOFC stack **102** through air conduit **302C**.

(15) Anode exhaust (e.g., fuel exhaust) generated in the SOFC stack **102** is provided to the anode recuperator **110** through anode exhaust conduit **308A**. The anode exhaust may contain unreacted fuel and may also be referred to herein as fuel exhaust. The anode exhaust may be provided from the anode recuperator **110** to a shift reactor **180**, such as an optional water gas shift (WGS) reactor, by anode exhaust conduit **308B**. In some embodiments, the reactions of WGS reactor may alternatively be reacted in a low-temperature shift (LTS) reactor of the fuel exhaust processor **400**. The water injector **160** may be fluidly connected to the anode exhaust conduit **308B**. The anode exhaust may be provided from the shift reactor **180** to the anode exhaust cooler **140** by anode exhaust conduit **308C**. The anode exhaust heats the air inlet stream in the anode exhaust cooler **140** and may then be provided from the anode exhaust cooler **140** to the fuel exhaust processor **400**.

(16) In particular, the anode exhaust may be output from the anode exhaust cooler **140** to the fuel exhaust processor **400** by a first recycling conduit **310A**. In some embodiments, anode exhaust may be provided to the fuel exhaust processor **400** by an optional second recycling conduit **310B**. In particular, the second recycling conduit **310B** may be configured to provide hotter anode exhaust to the fuel exhaust processor **400** than the first recycling conduit **310A**, since anode exhaust is cooled in the anode exhaust cooler **140** prior to entering the first recycling conduit **310A**. In some configurations, anode exhaust can flow through both first recycling conduit **310A** and second recycling conduit **310B**.

(17) The shift reactor **180** may be any suitable device that converts components of the fuel exhaust into free hydrogen (H₂) and/or water. For example, the shift reactor **180** may comprise a tube or conduit containing a catalyst that converts carbon monoxide (CO) and water vapor in the fuel exhaust stream into carbon dioxide and hydrogen, via the water gas shift reaction (CO+H₂O→CO₂+H₂). Thus, the shift reactor **180** increases the amount of hydrogen and carbon

dioxide in the anode exhaust and decreases the amount of carbon monoxide in the anode exhaust. For example, the shift reactor **180** may reduce the amount of carbon monoxide in the anode exhaust to about 5% by volume or less, such as about 4% or less, or about 3% or less. The catalyst may be any suitable catalyst, such as an iron oxide or a chromium-promoted iron oxide catalyst.

(18) Cathode exhaust generated in the SOFC stack **102** flows to the ATO **130** through cathode exhaust conduit **304A**. The vortex generator **172** may be disposed in the cathode exhaust conduit **304A** and may be configured to swirl the cathode exhaust. The ATO fuel conduit **304A** may be fluidly connected to the vortex generator **172** or to the cathode exhaust conduit **304A** or the ATO **130** downstream of the vortex generator **172**. The swirled cathode exhaust may mix with hydrogen output from the fuel exhaust processor **400** at the ATO **130** (e.g., at an ATO injector space). The mixture may be oxidized in the ATO **130** to generate ATO exhaust. The ATO exhaust flows from the ATO **130** to the cathode recuperator **120** through the cathode exhaust conduit **304B**. Exhaust flows from the cathode recuperator **120** and out of the hotbox **100** through cathode exhaust conduit **304C**.

(19) Water flows from a water source **206**, such as a water tank or a water pipe, to the water injector **160** through the water conduit **306**. The water injector **160** injects water directly into first portion of the anode exhaust provided in the anode exhaust conduit **308C**. Heat from the first portion of the anode exhaust (also referred to as a recycled anode exhaust stream) provided in the anode exhaust conduit **308C** vaporizes the water to generate steam. The steam mixes with the anode exhaust, and the resultant mixture is provided to the anode exhaust cooler **140**. The mixture is then routed through the fuel exhaust processor **400** and provided to the mixer **210**. The mixer **210** is configured to mix natural gas (or CPOx effluent if the CPOx is lit) and anode recycle from the stream of the anode recycle blower **212**. This humidified fuel mixture may then be heated in the anode recuperator **110** by the anode exhaust, before being provided to the SOFC stack **102**. The system **10** may also include one or more fuel reforming catalysts **112**, **114**, and **116** located inside and/or downstream of the anode recuperator **110**. The reforming catalyst(s) partially (e.g., 15%, 20%, etc.) reform the humidified fuel mixture before it is provided to the SOFC stack **102**.

(20) The system **10** may further include a system controller **225** configured to control various elements of the system **10**. The system controller **225** may include a central processing unit configured to execute stored instructions. For example, the system controller **225** may be configured to control fuel and/or air flow through the system **10**, according to fuel composition data.

(21) Fuel Exhaust Processors

(22) FIG. 2 is a schematic view showing components of the fuel exhaust processor **400**, according to various embodiments of the present disclosure. Referring to FIGS. 1 and 2, the fuel exhaust processor **400** may include a hydrogen separator **410**, a system controller **425**, a splitter **440**, a low temperature shift reactor **450**, and a heat exchanger **444**. The system controller **425** may be a central processing unit configured to execute stored instructions. For example, the system controller **425** may be configured to control anode exhaust, hydrogen and/or carbon dioxide flow through the fuel exhaust processor **400**. In some embodiments, the system controller **425** may be operatively connected to the system controller **225** of the SOFC system **10**, such that the system controller **425** may control the fuel exhaust processor based on operating conditions of the SOFC system **10**.

(23) The splitter **440** may be configured to receive anode exhaust from the first recycling conduit **310A**. The splitter **440** may be fluidly connected to the hotbox **100** and the hydrogen separator **410**. For example, a first return conduit **406A** may fluidly connect an outlet of the splitter **440** to the hotbox **100**, and a first separator conduit **401A** and a second separator conduit **401B** may fluidly connect an outlet of the splitter **440** to the hydrogen separator **410**. In particular, a first portion of the anode exhaust may be output from the splitter **440** and provided to the shift reactor **450** via the first separator conduit **401A**, and anode exhaust output from the shift reactor **450** may be supplied

to the hydrogen separator **410** by the second separator conduit **401B**. A second portion of the anode exhaust may be output from an outlet of the splitter **440** to the first return conduit **406A**. Anode exhaust output from the fuel exhaust processor **400** may be move through the first return conduit **406A** to the mixer **210** of the SOFC system **10**, by the anode recycle blower **212**. However, the anode recycle blower **212** may be disposed in any other suitable location.

(24) The shift reactor **450** may be a WGS reactor similar to the shift reactor **180**, but may configured to operate at a lower temperature than the shift reactor **180**. Accordingly, the shift reactor **180** may be referred to as a high temperature shift reactor, and the shift reactor **450** may be referred to as a low temperature shift reactor. The shift reactor **450** may be configured to further reduce the carbon monoxide content of the anode exhaust provided to the fuel exhaust processor **400**. For example, the shift reactor **450** may be configured to reduce the carbon monoxide content of the anode exhaust to less than about 0.3% by volume, such as less than about 0.2%, or less than about 0.1%.

(25) Purified anode exhaust (e.g., low carbon monoxide content anode exhaust) output from the shift reactor **450** may be provided to the hydrogen separator **410** by a second separator conduit **401B**. The heat exchanger **444** may be operatively connected to the second separator conduit **401B** and may be configured to cool anode exhaust passing there through. For example, the heat exchanger **444** may include fans and/or cooling fins configured to transfer heat to air supplied thereto. Accordingly, the heat exchanger **444** may be configured to cool the anode exhaust, in order to prevent overheating and/or damage to the hydrogen separator **410**. In some embodiments, the heat exchanger **444** may be omitted. For example, if the shift reactor **450** includes an internal cooling system, as disclosed below with respect to FIGS. **4A** and **4B**, the heat exchanger **444** may optionally be omitted.

(26) In various embodiments, the fuel exhaust processor **400** may be fluidly connected to multiple SOFC systems **10**. For example, the fuel exhaust processor **400** may be configured to process anode exhaust output from two or more fuel cell systems, and may be configured to return hydrogen rich fuel streams to both fuel cell systems.

(27) The hydrogen separator **410** may include one or more hydrogen pumps, which may each include electrochemical hydrogen pumping cells **420**. For example, as shown in FIG. **2**, the hydrogen separator **410** may include a first hydrogen pump **414A**, a second hydrogen pump **414B**, and a third hydrogen pump **414C**, that each comprise stacked hydrogen pumping cells **420**. However, the present disclosure is not limited to any particular number of hydrogen pumps. For example, in various embodiments, the first hydrogen pump **414A** and the second hydrogen pump **414B** may be combined into a single stack of hydrogen pumping cells **420**. In other embodiments, the first, second, and third hydrogen pumps **414A**, **414B**, **414C** may be combined into a single stack of hydrogen pumping cells **420**.

(28) In some embodiments, the first hydrogen pump **414A** may include a larger number of hydrogen pumping cells **420** than the second and/or third hydrogen pumps **414B**, **414C**. For example, the first hydrogen pump **414A** may include twice the number of hydrogen pumping cells **420** as the second hydrogen pump **414B** and/or the third hydrogen pump **414C**.

(29) In still other embodiments, the fuel exhaust processor **400** may output only a single hydrogen stream. For example, the third hydrogen pump **414C** may be omitted. In particular, heat generated by exothermic reactions in the ATO **130** may be used to offset heat losses due to endothermic fuel reformation reactions occurring in the anode recuperator **110**, by using the ATO exhaust to heat air provided to the fuel cell stack **102** in the cathode recuperator **120**. When there is no H₂ fuel fed to the ATO **130**, then there is no exothermic reaction in the ATO **130**. Accordingly, when the SOFC stacks are operated at steady state conditions where heat from the ATO **130** is not needed, then the fuel stream to the ATO **130** can be omitted.

(30) The second separator conduit **401B** may provide anode exhaust to an anode inlet of the first hydrogen pump **414A**. An anode outlet of the first hydrogen pump **414A** may be fluidly connected

to an anode inlet of the second hydrogen pump **414B** by a first exhaust conduit **402A**. An anode outlet of the second hydrogen pump **414B** may be fluidly connected to an anode inlet of the third hydrogen pump **414C**, by a second exhaust conduit **402B**. An anode outlet of the third hydrogen pump **414C** may be fluidly connected to the carbon dioxide storage device **50**, by a carbon dioxide storage conduit **52**.

(31) The carbon dioxide storage device **50** may include a carbon dioxide processor and a carbon dioxide storage tank. The processor may operate to compress and/or cool a carbon dioxide stream received from the fuel exhaust processor **400**. The processor may be a condenser and/or dryer configured to remove water from the carbon dioxide stream. The carbon dioxide stream may be provided to the carbon dioxide storage device **50** in the form of a vapor, liquid, solid or supercritical carbon dioxide. The carbon dioxide storage device **50** also may condense the carbon dioxide into a liquid phase after compression.

(32) A first hydrogen conduit **404A** may be fluidly connected to a cathode outlet of the first hydrogen pump **414A**, a second hydrogen conduit **404B** may be fluidly connected to a cathode outlet of the second hydrogen pump **414B**, and a third hydrogen conduit **404C** may be fluidly connected to a cathode outlet of the third hydrogen pump **414C**. The first hydrogen conduit **404A** may be fluidly connected to a first return conduit **406A**, and the second hydrogen conduit **404B** may be fluidly connected to the first hydrogen conduit **404A**. In particular, the first return conduit **406A** may be configured to provide hydrogen extracted from the anode exhaust by the first hydrogen pump **414A**, the second hydrogen pump **414B**, and or the third hydrogen pump **414C** to the mixer **210**, such that the hydrogen may be recycled to the SOFC stack **102**.

(33) The third hydrogen conduit **404C** may be fluidly connected to the SOFC system **10** by a second return conduit **406B**. In particular, the second return conduit **406B** may be configured to provide hydrogen extracted from the anode exhaust by the third stack **414C** to the second return conduit **406B**, which may provide the hydrogen to the ATO **130**.

(34) In some embodiments, an optional fourth hydrogen conduit **404D** may fluidly connect the third hydrogen conduit **404C** to the first hydrogen conduit **404A**. An optional fifth hydrogen conduit **404E** may fluidly connect the second hydrogen conduit **404B** to the third hydrogen conduit **404C**. An optional hydrogen storage conduit **56** may fluidly connect the first hydrogen conduit **404A** to the hydrogen storage device **54**.

(35) The hydrogen storage device **54** may include, for example, a condenser and a hydrogen storage tank. The condenser may be an air-cooled or water-enhanced, air-cooled condenser and/or heat exchanger configured to cool a hydrogen stream received from the fuel exhaust processor **400**, to a temperature sufficient to condense water vapor in the hydrogen stream. The hydrogen storage device **54** may further include compression to the desired storage pressure. A wide range of pressure above ambient is feasible, but is likely set to a value that corresponds with allowed piping standards (e.g., 150 psig, 300 psig, 600 psig, 1500 psig, etc.)

(36) The first return conduit **406A** may fluidly connect the splitter **440** to the mixer **210** of the SOFC system **10**. The second return conduit **406B** may fluidly connect the first separator conduit **401A** to the ATO **130**, and may also be fluidly connected to the third hydrogen conduit **404C**. In other embodiments, the second return conduit **406B** may be fluidly connected to an outlet of the splitter **440**. A third return conduit **406C** may fluidly connect the second separator conduit **401B** to the second return conduit **406B**.

(37) In various embodiments, the fuel exhaust processor **400** may include various valves to control fluid flow. For example, a first separator conduit valve **401V1** and a second separator conduit valve **401V2** may be respectively configured to control anode exhaust flow through the first and second separator conduits **401A**, **401B**. A first hydrogen conduit valve **404V1**, a second hydrogen conduit valve **404V2**, a third hydrogen conduit valve **404V3**, a fourth hydrogen conduit valve **404V4**, and a fifth hydrogen conduit valve **404V5** may be configured to respectively control hydrogen flow through the first, second, third, fourth, and fifth hydrogen conduits **404A**, **404B**, **404C**, **404D**,

404E. A hydrogen storage valve **56V**, such as a two way valve, may be configured to control hydrogen flow from the first hydrogen conduit **404A** into the hydrogen storage conduit **56**. A second return conduit valve **406V2** and a third return conduit valve **406V3**, may be configured to respectively control anode exhaust flow through the second and third return conduits **406B**, **406C**. (38) In some embodiments, the fuel exhaust processor **400** may be fluidly connected to multiple hotboxes **100**. For example, the splitter **440** may receive anode exhaust from multiple recycling conduits **310A/310B**, and may be fluidly connected to multiple return conduits **406A**, **406B**. For example, the recycling conduits **310A/310B** and the first and second return conduits **406A**, **406B** may be branched and connected to different hotboxes **100**.

(39) Hydrogen Pumping Cells

(40) FIG. 3 is a cross-sectional view of a hydrogen pumping cell **420** that may be included in the fuel exhaust processor **400**, according to various embodiments of the present disclosure. Referring to FIG. 4, the hydrogen pumping cell **420** may be polymer electrolyte (PEM) cells that include an anode gas diffusion layer (GDL) **422**, a cathode GDL **424**, and a membrane electrode assembly (MEA) disposed there between. The MEA may include the GDL, an anode **426**, a cathode **428**, and a polymer membrane **430** disposed there between. The hydrogen pumping cell **420** may be disposed between bipolar plates **432**. The bipolar plates **432** may include channels to deliver reactants to the hydrogen pumping cells **420** disposed thereon. The bipolar plates **432** may be formed of material such as graphite.

(41) The GDLs **422**, **424** may be formed of a porous medium configured to distribute or remove the reactants received from adjacent bipolar plates **432**. The GDLs may comprise, for example, carbon paper treated with a hydrophobic material, such as polytetrafluoroethylene (PTFE), to reduce water accumulation. The anode **426** may be configured to oxidize hydrogen. The cathode **428** may be configured to evolve hydrogen (i.e., convert $2H_{2(g)} + O_{2(g)}$ into $H_2O_{(l)}$). For example, the anode **426** and the cathode **428** may include a Pt/C catalyst. In some embodiments, the cathode **428** may have a higher or lower catalyst loading than the anode **426**, for example. The catalyst type (e.g., CO tolerant catalyst on the cathode and/or anode side) and loading may vary at anode **426** and/or cathode **428**. The membrane **430** may be configured to transport ions. For example, the membrane **430** may include an ionomer such as Nafion. When an electrical potential is applied between the anode **426** and the cathode **428**, hydrogen ions are generated at the anode **426**, the hydrogen ions are driven through the membrane **430** by the applied electrical potential, and the hydrogen ions are recombined to evolve hydrogen gas at the cathode **428**. In some embodiments, the anodes **426** may be carbon monoxide tolerant anodes, as disclosed in Indian Provisional Application number 2021-11016645 filed Mar. 8, 2021 and U.S. application Ser. No. 17/715,353, each of which is incorporated herein by reference in its entirety.

(42) Shift Reactor With Active Cooling

(43) FIG. 4A is a perspective view of a low-temperature shift reactor **450** that may be included in the fuel exhaust processor **400** of FIG. 2, according to various embodiments of the present disclosure, and FIG. 4B is a cross-sectional view of the shift reactor **450**. Referring to FIGS. 4A and 4B, the shift reactor **450** may include a cover **451**, an inlet **452**, an outlet **454**, a first chamber **456**, a second chamber **458**, cooling conduits **460**, a fan housing **462**, at least one fan **464**, a first screen **466**, a second screen **468**, a first catalyst bed **470**, a second catalyst bed **472**, and a control unit **474**.

(44) The cover **451** may cover the first chamber **456**, and the first chamber **456** may be disposed over the second chamber **458**. The cooling conduits **460** may be disposed between the first and second chambers **456**, **458**. The fan housing **462** and the fans **464** may be connected to the cooling conduits **460**. The first screen **466** may be disposed adjacent the bottom of the first chamber **456**, and the second screen **468** may be disposed adjacent to the bottom of the second chamber **458**. The first catalyst bed **470** may be disposed in the first chamber **456** and on the first screen **466**, and the second catalyst bed **472** may be disposed in the second chamber **458** and on the second screen **468**.

(45) The first and second catalyst beds **470**, **472** may include any suitable WGS reaction catalysts, such as an iron oxide or a chromium-promoted iron oxide catalyst. Depending on the temperature range, zinc-copper or ferrochromium alloy catalysts or other known catalysts may be used. The catalyst may have an acceptable catalytically active at temperature ranging from about 200° C. to about 300° C. Alternatively, the catalyst can continue to be active to as low as 150° C. in some instances. In some embodiments, the first and second catalyst beds **470**, **472** may include the same catalyst or different catalysts. In various embodiments, the shift reactor **450** may be configured to reduce the carbon monoxide content of the anode exhaust to about 0.3% or less.

(46) In various embodiments, the first catalyst bed **470** may not completely fill the first chamber **456**. In particular, a first space S1 may be formed between the upper surface of the first catalyst bed **470** and a lower surface of the cover **451**. The first screen **466** may separate the first catalyst bed **470** and the cooling conduits **460**, and the top surface of the second catalyst bed **472** may be spaced apart from the cooling conduits **460**, such that a second space S2 is formed around the cooling conduits **460**, between the first and second chambers **456**, **458**. Similarly, the second screen **468** may separate the second catalyst bed **472** from the bottom of the second chamber **458**, such that a third space S3 is formed under the second screen **468**.

(47) The inlet **452** may be configured to provide anode exhaust to the first chamber **456**. In particular, the anode exhaust may be provided to the first space S1, before entering the first catalyst bed **470**. Accordingly, the anode exhaust may be dispersed in the first space S1 and uniformly distributed in the first catalyst bed **470**. The anode exhaust may then pass through the first screen **466** and into the second space S2, where the anode exhaust may be dispersed around the cooling conduits **460**, before entering the second catalyst bed **472**. The cathode exhaust may then flow through the second catalyst bed **472**, the second screen **470**, and into the third space S3, before entering the outlet **454**.

(48) The fans **464** may be variable speed fans configured to force air into the fan housing **462** and through the cooling conduits **460**. The fan housing **462** may be triangular in cross-section and may be configured to channel the air output from the relatively large diameter fans **464** into the relatively small diameter the cooling conduits **460**. Air flowing through the cooling conduits **460** may reduce the temperature of the cooling conduits **460**, which may be heated by interaction with the anode exhaust. As such, the cooling conduits **460** may be configured to reduce the temperature of the anode exhaust, by transferring heat to the air flowing there through. In some embodiments, an optional air filter (not shown) may be disposed within the fan housing **462**.

(49) In various embodiments, the control unit **474** may be configured to control the speed of the fans **464**, based on the temperature of the anode exhaust flowing through the shift reactor **450** and/or a temperature of the catalyst beds **470**, **472**. In particular, exothermic oxidation reactions occurring during operation of the shift reactor **450** may increase the temperature of the anode exhaust flowing there through. During steady state operation, the control unit **474** may be configured to operate the fan at a speed sufficient maintain the temperature of the anode exhaust within a desired temperature range, such as a temperature ranging from about 200° C. to about 250° C., such as a temperature ranging from about 210° C. to about 240° C.

(50) In particular, the speed of the fans **464** may be controlled based on an anode exhaust flow rate through the shift reactor **450**, with higher fan speeds being utilized at higher anode exhaust flow rates. In other embodiments, the fan speed may be controlled based on a temperature of the shift reactor **450** and/or a temperature of anode exhaust flowing past the cooling conduits **460** and/or output from the shift reactor **450**. For example, the control unit **474** may include, or be operatively connected to, a temperature sensor, such as a thermocouple, configured to detect the anode exhaust temperature. For example, the temperature sensor may be configured to detect the temperature of the anode exhaust adjacent to the cooling conduits **460** and/or adjacent to the top of the second catalyst bed **472**. In some embodiments, the shift reactor **450** may include multiple temperature sensors, in order to provide temperature detection redundancy, for example.

(51) In some embodiments, the fans **464** may not be operated if relatively cool anode exhaust is provided to the shift reactor **450**, such as during system startup. However, in some embodiments, the fans **464** may be operated during system startup, in order to prevent excessive heat accumulation due exothermic reactions that may occur due to adsorption of gas species to the catalyst material. In some embodiments, the shift reactor **450** may optionally include a heating element (not shown), such as heating tape disposed on an outer surface of the shift reactor **450**. The heating element may be used, for example, during system startup, in order to heat the shift reactor **450** (e.g., to heat the first and/or second catalyst beds **470**, **472**) to a desired operating temperature.

(52) In some embodiments, the first screen **466** and/or the cover **451** may be removable, so as to facilitate catalyst loading. For example, the cover **451** and the first screen **466** may be removed, a catalyst material may be filled between the cooling conduits **460** to form the second catalyst bed **472** in the second chamber **458**. The first screen **466** may be installed and secured via tack welding or mechanical fasteners, and then a catalyst material may be filled into the first chamber **456** to form the first catalyst bed **470**. The cover **451** may then be attached.

(53) The cooling conduits **460** may be separated by a gap ranging from about 2 to about 7 mm, such as from about 3 to about 5 mm, in order to permit loading of a catalyst material into the second chamber **458**. The cooling conduits **460** may have a triangular pitch or a rectangular pitch, in some embodiments. In various embodiments, the cooling conduits **460** may include heat transfer structures, such as external fins or the like, to increase heat transfer. In various embodiments, the shift reactor **450** may include a single row or cooling conduits **460**, as shown in FIGS. **4A** and **4B**. In other embodiments, the shift reactor **450** may include multiple rows of cooling conduits **460** in the second space **S2**. In other embodiments, the shift reactor **450** may include more than two catalyst beds, and at least one row of cooling conduits disposed between each pair of catalyst beds. For example, the shift reactor **450** may include three catalyst beds and two rows of cooling conduits.

(54) Methods of SOFC System Operation Including Fuel Exhaust Processing

(55) FIG. **5** is a schematic view showing fuel flow through of the SOFC system **10** during a startup mode, according to various embodiments of the present disclosure, wherein fuel flow is shown by dashed lines. Referring to FIGS. **1** and **5**, during startup, various components of the SOFC system **10** may heated from ambient temperatures to operating temperatures. Accordingly, the SOFC system may be configured to heat components as quickly as possible to operating temperatures.

(56) In particular, anode exhaust may be output from the hotbox **100** to the splitter **440** of the fuel exhaust processor **400**, via the second recycling conduit **310B**. However, in some embodiments, the first recycling conduit **310A** may be used to provide the anode exhaust. The splitter **440** may output a first portion of the anode exhaust back to the hotbox **100**, via the first return conduit **406A**. In particular, the first portion of the anode exhaust may be used to maintain a carbon to oxygen ratio in fuel provided to the SOFC stack **102**.

(57) The splitter **440** may output a second portion of the anode exhaust to the hotbox **100**, via the second return conduit **406B**. The first portion of the anode exhaust may be provided to the SOFC stack **102**, and the second portion of the anode exhaust may be provided to the ATO **130**.

(58) In particular, the system controller **425** may close the first separator conduit valve **401V1** and the third return conduit valve **406V3**, and may open the second return conduit valve **406V2**, in order to direct the second portion of the anode exhaust away from the hydrogen separator **410** and back to the ATO **130**. In other words, the hydrogen separator **410** may not be operated during system startup.

(59) FIG. **6** is a schematic view showing fuel flow through of the SOFC system **10** during a low-current steady-state mode, according to various embodiments of the present disclosure, wherein fuel flow is show by dashed lines. Referring to FIGS. **1** and **6**, if a relatively low current load, for example a current load of less than about 25 amps, is applied to the hotbox **100** and/or stacks **102** included therein, the amount of heat generated in the hotbox may be insufficient for stable power

generation, without additional heat being generated by the ATO **130**. Accordingly, the system controller **425** may be configured to provide anode exhaust from the fuel exhaust processor **400** to the ATO **130**.

(60) For example, anode exhaust may be output from the hotbox **100** to the splitter **440**, via the first recycling conduit **310A**. A first portion of the anode exhaust may be output from the splitter **440** and returned to the hotbox **100**, via the first return conduit **406A**.

(61) A second portion of the anode exhaust is output from the splitter **440** to the shift reactor **450**, via the first separator conduit **401A**. The anode exhaust output from the shift reactor **450** may be provided to the optional heat exchanger **444**, via the second separator conduit **401B**, before being provided to the third return conduit **406C**. In the alternative, the anode exhaust may be provided from the second separator conduit **401B** directly to the third return conduit **406C**. The anode exhaust may then be provided to the hotbox **100** for use in the ATO, via the second return conduit **406B**.

(62) Accordingly, during the low-current mode, the hydrogen separator **410** is not provided with anode exhaust and is not operated. In particular, the system controller **425** may close the second separator conduit valve **401V2**, the second return conduit valve **406V2**, and the first hydrogen conduit valve **404V1**, to isolate the hydrogen separator **410**, and may open the first separator conduit valve **401V1** and the third return conduit valve **406V3**, to provide anode exhaust to the ATO **130**.

(63) FIG. 7 is a schematic view showing fuel flow through of the SOFC system **10** during a high-current steady-state mode, according to various embodiments of the present disclosure, wherein fuel flow is shown by dashed lines. Referring to FIGS. 1, 2, and 7, if a relatively high current load, for example a current load of at least 25 amps, is applied to the hotbox **100** and/or stacks **102** included therein, an amount of heat may be generated in the hotbox **100** may be sufficient or nearly sufficient for stable power generation. As such, the heat output and fuel consumption of the ATO **130** may be minimized.

(64) For example, anode exhaust may be output from the hotbox **100** to the splitter **440**, via the first recycling conduit **310A**. A first portion of the anode exhaust may be output from the splitter **440** and returned to the hotbox **100**, via the first return conduit **406A**.

(65) A second portion of the anode exhaust is output from the splitter **440** to the shift reactor **450**, via the first separator conduit **401A**. The shift reactor **450** may reduce the carbon monoxide content of the anode exhaust from about 5% by volume to less than about 0.3% by volume. In some embodiments, this further reduction in carbon monoxide content may reduce and/or prevent deactivation of anode catalysts of the hydrogen separator **410**.

(66) For example, the shift reactor **450** may be actively cooled during operation, such that the anode exhaust is output from the shift reactor **450** at a temperature of less than about 240° C., such as less than about 220° C., or less than about 200° C., which may be sufficient to prevent damage to the membranes of the hydrogen pumping cells **420**. Accordingly, when the actively cooled shift reactor **450** is used, the heat exchanger **444** may be omitted in some embodiments.

(67) However, in other embodiments, the heat exchanger **444** may be used to further reduce the temperature of the anode exhaust output from the shift reactor **450**. For example, the heat exchanger **444** may reduce the temperature of the anode exhaust to about 100° C. or less, such as to a temperature of from about 80° C. to about 50° C., from about 75° C. to about 55° C., or to about 65° C. The heat exchanger **444** may cool the anode exhaust by transferring heat to ambient air.

(68) The anode exhaust may be output from the shift reactor **450** and/or the heat exchanger **444** to the anode inlet of the first hydrogen pump **414A**, via the second separator conduit **401B**. In particular, the system controller **425** may close the second return conduit valve **406V2** and the third return conduit valve **406V3**, and may open the first and second separator conduit valves **401V1**, **401V2**, such that the second portion of the anode exhaust is provided only to the fuel exhaust processor **400**.

(69) The anode exhaust may be distributed to the anodes of each hydrogen pumping cell **420** in the first hydrogen pump **414A**. Power may be provided to the hydrogen pumping cells **420** to separate hydrogen from the anode exhaust. The evolved hydrogen may be output from the cathode outlet of the first hydrogen pump **414A** to the first return conduit **406A**, via the first hydrogen conduit **404A**. The remaining anode exhaust may be output from the anode outlet of the first hydrogen pump **414A** to the anode inlet of the second hydrogen pump **414B**, via the first exhaust conduit **402A**.

(70) Power may be applied to the hydrogen pumping cells **420** of the second hydrogen pump **414B** to separate hydrogen from the anode exhaust flowing therethrough. The separated hydrogen may be output from the cathode outlet of the second hydrogen pump **414B** to the first hydrogen conduit **404A**, via the second hydrogen conduit **404B**. The remaining anode exhaust may be output from the anode outlet of the second hydrogen pump **414B** to the anode inlet of the third hydrogen pump **414C**, via the second exhaust conduit **402B**.

(71) Power may be applied to the hydrogen pumping cells **420** of the third hydrogen pump **414C** to separate hydrogen from the anode exhaust flowing there through. The separated hydrogen may be output from the cathode outlet of the third hydrogen pump **414C** to the second return conduit **406B**, via the third hydrogen conduit **404C**. The remaining anode exhaust may be output from the anode outlet of the third hydrogen pump **414C** to the third hydrogen conduit **404C**. In some embodiments, the remaining anode exhaust may comprise at least 95%, such as at least 97% or at least 98% by volume carbon dioxide. Accordingly, a purified carbon dioxide stream may be output from the fuel exhaust processor **400** and stored in the carbon dioxide storage device **50**. The stored carbon dioxide may be provided to carbon dioxide consumers, such as the beverage industry, in order to recycle the carbon dioxide and provide supplemental income.

(72) A first hydrogen stream (e.g., hydrogen-enriched fuel stream), including the hydrogen output from the first hydrogen pump **414A** and the second hydrogen pump **414B**, may be output to the hotbox **100** via the first hydrogen conduit **404A**, the second hydrogen conduit **404B**, and the first return conduit **406A**. In particular, the first hydrogen stream may be provided to the mixer **210** and recycled for use in to the fuel cell stack **102**.

(73) In the alternative, all or a portion of the first hydrogen stream may be provided to the hydrogen storage via the hydrogen storage conduit **56** and stored in the hydrogen storage device **54**. In some embodiments, the hydrogen storage valve **56V** may be used to control how much of the first hydrogen stream is stored in the hydrogen storage device **54** and how much is provided to the SOFC system **10**.

(74) A second hydrogen stream (e.g., hydrogen-enriched fuel stream), including the hydrogen output from the third hydrogen pump **414C** via the third hydrogen conduit **404C**, may be provided to the hotbox **100** via the third hydrogen conduit **404C** and the second return conduit **406B**. In particular, the second hydrogen stream may be provided to the ATO **130** for oxidation by the second return conduit **406B**.

(75) A high-purity carbon dioxide stream may be output from the hydrogen separator **410** to the carbon dioxide storage device **50**, via the carbon dioxide storage conduit **52**. For example, the carbon dioxide stream may be at least 98 volume percent carbon dioxide. In some instances, the purity of the carbon dioxide stream may be less than 98 volume percent if that is compatible with the downstream use, such as greater than 95 volume percent.

(76) FIG. **8** is a schematic view showing fuel flow through of the SOFC system **10** during an alternative steady-state mode, according to various embodiments of the present disclosure, wherein fuel flow is show by dashed lines. The alternative high-current steady-state mode may be similar to the high-current steady-state mode of FIG. **7**. As such, only the difference there between will be discussed in detail.

(77) Referring to FIGS. **1**, **2**, and **8**, it has been determined that by providing hydrogen rich recycled fuel to the hotbox **100**, fuel reformation reactions may be correspondingly reduced, thereby reducing heat loss within the SOFC system **10**. As a result, fuel cell stack operating

temperatures may be maintained during steady-state operation, without providing fuel to the ATO **130**.

(78) Accordingly, the system controller **425** may be configured to close the third hydrogen conduit valve **404V3** and open the fourth hydrogen conduit valve **404V4**, such that hydrogen extracted by the third hydrogen pump **414C** is diverted into the fourth hydrogen conduit **404D** and provided to the first return conduit **406A**, via the first hydrogen conduit **404A**. In other words, the hydrogen output from the third hydrogen pump **414C** may be added to the first hydrogen stream provided to the fuel cell stack **102**. In other words, a second hydrogen stream may not be provided to the ATO **130**.

(79) In some embodiments, the SOFC system **10** may be operated in a hydrogen generation mode to maximize hydrogen extraction and/or storage. In particular, the system controller **225** may be configured to increase hydrogen extraction by the fuel exhaust processor **400**, by decreasing the fuel utilization rate of the SOFC stack **102** (e.g., a ratio of current drawn from the SOFC stack **102** to a flow rate of fresh fuel supplied to the SOFC stack **102** from the fuel inlet **300**).

(80) For example, the fuel utilization rate may be decreased by decreasing the current drawn from the SOFC stack **102** and/or by increasing the flow rate of fresh fuel to SOFC stack **102**, such that the anode exhaust output to the fuel exhaust processor **400** has a higher hydrogen content. The higher hydrogen content of the anode exhaust may increase the amount of hydrogen extracted by the hydrogen separator **410**. Thus, the hydrogen generation mode may include reducing a fuel utilization rate to increase hydrogen extraction.

(81) In some embodiments, the hydrogen generation mode may utilize the hydrogen flow configuration shown in FIG. 7. In particular, hydrogen generated by the third hydrogen pump **414C** may be provided to the ATO. Since the amount of hydrogen extracted by the third hydrogen pump **414C** may be relatively low, as compared to the amounts of hydrogen extracted by the first and second hydrogen pumps **414A**, **414B**, the rate of hydrogen generation and storage may not be significantly decreased.

(82) In the various embodiments, three hydrogen pumps **414A**, **414B**, **414C** are shown, but the embodiments are not so limited. In some embodiments, varying numbers of hydrogen pumps may be used. For example, two hydrogen pumps may be used in some configurations. In the two hydrogen pump configuration, the first hydrogen pump and the second hydrogen pump output hydrogen to one or more components of the hotbox as fuel. Any of the hydrogen pumps may be configured to send the hydrogen stream to ATO **130** or back to hotbox **100** as fuel. Independent of the number of hydrogen pumps used, it is preferred to provide the output of the hydrogen pumps back to hotbox **100** as fuel, as this is thermally stable under most conditions. If thermal stability (e.g. due to low current SOFC operation) is not achievable, then the hydrogen from any of the hydrogen pumps may be output to ATO **130** either steadily, or for periodic timed durations (e.g. 1 minute out of 5, etc).

(83) The preceding description of the disclosed aspects is provided to enable any person skilled in the art to make or use the present invention. Various modifications to these aspects will be readily apparent to those skilled in the art, and the generic principles defined herein may be applied to other aspects without departing from the scope of the invention. Thus, the present invention is not intended to be limited to the aspects shown herein but is to be accorded the widest scope consistent with the principles and novel features disclosed herein.

Claims

1. A fuel cell system comprising: a hotbox; a fuel cell stack disposed in the hotbox; an anode tail gas oxidizer (ATO) disposed in the hotbox; and a fuel exhaust processor fluidly connected to the hotbox and comprising: a first hydrogen pump configured to extract hydrogen from the anode exhaust received from the fuel cell stack and to output the hydrogen to a first hydrogen stream

provided to the fuel cell stack; a second hydrogen pump configured to extract hydrogen from anode exhaust output from the first hydrogen pump and to output the hydrogen to the first hydrogen stream; and a third hydrogen pump configured to extract hydrogen from anode exhaust output from the second hydrogen pump and to output the hydrogen to a second hydrogen stream provided to the ATO.

2. The fuel cell system of claim 1, further comprising a carbon dioxide storage device configured to store a carbon dioxide stream output from an anode outlet of the third hydrogen pump.

3. The fuel cell system of claim 1, further comprising a hydrogen storage device configured to store at least a portion of the first hydrogen stream.

4. The fuel cell system of claim 1, wherein: the first hydrogen pump comprises a first stack of hydrogen pumping electrochemical cells; the second hydrogen pump comprises a second stack of hydrogen pumping electrochemical cells; the third hydrogen pump comprises a third stack of hydrogen pumping electrochemical cells; and the first stack comprises a larger number of electrochemical cells than the second stack and the third stack; and the hydrogen pumping cells each comprise an electrolyte disposed between a cathode and an anode.

5. The fuel cell system of claim 1, wherein the fuel exhaust processor further comprises a splitter configured to receive anode exhaust output from the fuel cell stack, output a first portion of the anode exhaust to the fuel cell stack, and output a second portion of the anode exhaust to the first hydrogen pump.

6. The fuel cell system of claim 5, further comprising a high temperature shift reactor disposed in the hotbox and configured to reduce the amount of the carbon monoxide in the anode exhaust provided to the splitter, wherein the fuel exhaust processor further comprises a low temperature shift reactor configured to further reduce the amount of carbon monoxide in the anode exhaust product fed to the hydrogen pumps.

7. The fuel cell system of claim 6, wherein the fuel exhaust processor further comprises a heat exchanger configured to reduce the temperature of anode exhaust output from the low temperature shift reactor and provided to the first hydrogen pump.

8. The fuel cell system of claim 6, wherein the low temperature shift reactor comprises: a first chamber; a second chamber; cooling conduits disposed between the first chamber and the second chamber; a fan configured to force air through the cooling conduits; a first catalyst bed disposed in the first chamber; a second catalyst bed disposed in the second chamber; an inlet fluidly connected to the first chamber; and an outlet fluidly connected to the second chamber.

9. The fuel cell system of claim 8, wherein the low temperature shift reactor further comprises: a first screen disposed in the first chamber; and a second screen disposed in the second chamber, wherein the first catalyst bed is disposed on the first screen and the second catalyst bed is disposed on the second screen.

10. The fuel cell system of claim 9, wherein: a first space is formed in the first chamber above the first catalyst bed; a second space is formed around the cooling conduits; a third space is formed in the second chamber below the second screen; and the low temperature reactor is configured such that anodes exhaust flows through the inlet, into the first space, through the first catalyst bed, into the second space, through the second catalyst bed, into the third space, and then into the outlet.

11. The fuel cell system of claim 8, wherein the low temperature shift reactor further comprises: a temperature sensor configured to detect a temperature of anode exhaust flowing through the low temperature shift reactor; and a control unit configured to control a speed of the fan according to the temperature detected by the temperature sensor.

12. The fuel cell system of claim 6, further comprising: a first return conduit that fluidly connects an outlet of the splitter to the fuel cell stack; a first separator conduit that fluidly connects an outlet of the splitter to an inlet of the low temperature shift reactor; a second return conduit that fluidly connects the first separator conduit or an outlet of the splitter to the ATO; a second separator conduit that fluidly connects an outlet of the low temperature shift reactor to an anode inlet of the

first hydrogen pump; a third return conduit that fluidly connects the second separator conduit to the second return conduit; a first hydrogen conduit fluidly connecting a cathode outlet of the first hydrogen pump to the first return conduit; a second hydrogen conduit fluidly connecting a cathode outlet of the second hydrogen pump to the first return conduit; and a third hydrogen conduit fluidly connecting a cathode outlet of the third hydrogen pump to the second return conduit.

13. The fuel cell system of claim 12, further comprising: a fourth hydrogen conduit that fluidly connects the third hydrogen conduit to the second return conduit; and a fifth hydrogen conduit that fluidly connects the second hydrogen conduit to the second return conduit.

14. A fuel cell system comprising: a hotbox; a fuel cell stack disposed in the hotbox; an anode tail gas oxidizer (ATO) disposed in the hotbox; a recycling conduit configured to receive anode exhaust from the fuel cell stack; a splitter fluidly connected to the recycling conduit; a low temperature shift reactor; a hydrogen separator comprising: a first hydrogen pump; a second hydrogen pump that is fluidly connected to the first hydrogen pump; and a third hydrogen pump that is fluidly connected to the second hydrogen pump; a supply conduit that fluidly connects an outlet of the splitter to the hydrogen separator; a first separator conduit fluidly connecting the splitter to the low temperature shift reactor; a second separator conduit fluidly connecting the low temperature shift reactor to the first hydrogen pump; a first return conduit that fluidly connects an outlet of the splitter to the fuel cell stack; a second return conduit that fluidly connects an outlet of the splitter or the separator conduit to the ATO; and a third return conduit that fluidly connects the separator conduit to the second return conduit.

15. A method of using the fuel cell system of claim 14 in a startup mode, the method comprising: providing anode exhaust generated by the fuel cell stack to the separator through the recycling conduit; outputting a first portion of the anode exhaust from the separator to the fuel cell stack through the first return conduit; and outputting a second portion of the anode exhaust from the separator to the ATO through the second return conduit.

16. A method of using the fuel cell system of claim 14 in a low current mode, the method comprising: providing anode exhaust generated by the fuel cell stack to the separator through the recycling conduit; providing a first portion of the anode exhaust from an outlet of the splitter to the fuel cell stack through the first return conduit; providing a second portion of the anode exhaust from an outlet of the splitter to the low temperature shift reactor through the first separator conduit; and providing anode exhaust from an outlet of the low temperature shift reactor to the ATO through the second separator conduit, the third return conduit, and the second return conduit.

17. The method of claim 16, wherein: the providing anode exhaust from an outlet of the low temperature shift reactor to the ATO further comprises cooling the anode exhaust in the second separator conduit using a heat exchanger; and the method further comprises actively cooling the anode exhaust in the low temperature shift reactor using forced air.

18. A method of using the fuel cell system of claim 14 in a steady state mode, the method comprising: providing anode exhaust generated by the fuel cell stack to the separator through the recycling conduit; providing a first portion of the anode exhaust from an outlet of the splitter to the fuel cell stack through the first return conduit; providing a second portion of the anode exhaust from an outlet of the splitter to the low temperature shift reactor through the first separator conduit; providing anode exhaust from an outlet of the low temperature shift reactor to the hydrogen separator through the second separator conduit; providing a first hydrogen (H.sub.2) stream extracted from the anode exhaust by the first and second hydrogen pumps to the fuel cell stack through the first return conduit; and providing a second hydrogen stream extracted from the anode exhaust by the third hydrogen pump to the ATO through the second return conduit.

19. The method of claim 18, wherein the anode exhaust is sequentially provided to anodes of the first hydrogen pump, the second hydrogen pump, and the third hydrogen pump.

20. The method of claim 18, further comprising: decreasing a current load applied to the fuel cell stack and/or increasing a flow rate of fresh fuel to the fuel cell stack, in order to decrease a fuel

utilization rate of the fuel cell stack and to increase an amount of hydrogen extracted from the anode exhaust by the hydrogen separator; and storing the first hydrogen stream in a hydrogen storage device fluidly connected to the first return conduit.
