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Fuel cell system including catalyst ring anode tail gas oxidizer

Abstract

A fuel cell system anode tail gas oxidizer (ATO) includes an inner ATO wall, an outer ATO wall, and a first catalyst ring disposed in a chamber formed between the inner ATO wall and the outer ATO wall. The first catalyst ring includes an inner wall, an outer wall, and a matrix disposed between the inner wall and the outer wall and loaded with an oxidation catalyst.

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Background/Summary

FIELD

(1) Aspects of the present invention relate to fuel cell systems, and more particularly, to fuel cell systems including a catalyst ring anode tail gas oxidizer (ATO).

BACKGROUND

(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

(3) According to various embodiments, provided is a fuel cell system anode tail gas oxidizer (ATO) comprising: an inner ATO wall; an outer ATO wall; and a first catalyst ring disposed in a chamber formed between the inner ATO wall and the outer ATO wall, the first catalyst ring comprising: an inner wall; an outer wall; and a matrix disposed between the inner wall and the outer wall and loaded with an oxidation catalyst.

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 of a fuel cell system, according to various embodiments of the present disclosure.

(3) FIG. **2**A is a sectional view showing components of the hot box of the system of FIG. **1**, FIG. **2**B shows an enlarged portion of the system of FIG. **2**A, FIG. **2**C is a three dimensional cut-away view of a central column of the system of FIG. **2**A, and FIG. **2**D is a perspective view of an anode hub structure disposed below the central column of the system of FIG. **2**A, according to various embodiments of the present disclosure.

(4) FIGS. **3**A-**3**C are sectional views showing fuel and air flow through the central column of the system of FIG. **2**A, according to various embodiments of the present disclosure.

(5) FIG. **4** is a partial perspective view of the central column of the system of FIG. **2**A, according to various embodiments of the present disclosure.
(6) FIG. **5**A is a photograph showing an exemplary central column **400**, with the outer cylinder of the ATO removed, FIG. **5**B is a photograph showing a top perspective view of the catalyst ring of the ATO, and FIG. **5**C is a photograph showing a close up view of the top surface of a portion of the catalyst ring, according to various embodiments of the present disclosure.
(7) FIG. **5**D is a top view according to an alternative catalyst ring, according to various embodiments of the present disclosure.
(8) FIG. **6** is a perspective view of a modified ATO, according to various embodiments of the present disclosure.

DETAILED DESCRIPTION

(9) 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.
(10) 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.
(11) 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.
(12) 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 hot box **100** may contain fuel cell stacks **102**, such as a solid oxide fuel cell stacks 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.
(13) The hot box **100** may also contain an anode recuperator heat exchanger **110**, a cathode recuperator heat exchanger **120**, an anode tail gas oxidizer (ATO) **500**, an anode exhaust cooler heat exchanger **140**, a splitter **550**, a vortex generator **552**, 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., 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**.

(14) The CPOx reactor **200** receives a fuel inlet stream from a fuel inlet **300**, through fuel conduit **300**A. 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 **202** during system start-up. The fuel and/or air may be provided to the mixer **210** by fuel conduit **300**B. Fuel (e.g., the fuel inlet stream **1721** described below with respect to FIGS. **4**A-**4**C) flows from the mixer **210** to the anode recuperator **110** through fuel conduit **300**C. 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 stack **102** through fuel conduit **300**D.

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

(16) An anode exhaust stream (e.g., the fuel exhaust stream described below with respect to FIGS. **3**A-**3**C) generated in the stack **102** is provided to the anode recuperator **110** through anode exhaust conduit **308**A. 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 the splitter **550** by anode exhaust conduit **308**B. A first portion of the anode exhaust may be provided from the splitter **550** to the anode exhaust cooler **140** through the water injector **160** and the anode exhaust conduit **308**C. A second portion of the anode exhaust is provided from the splitter **550** to the ATO **500** through the anode exhaust conduit **308**D. The first portion of 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 mixer **210** through the anode exhaust conduit **308**E. The anode recycle blower **212** may be configured to move anode exhaust though anode exhaust conduit **308**E, as discussed below.

(17) Cathode exhaust generated in the stack **102** flows to the ATO **500** through exhaust conduit **304**A. The vortex generator **552** may be disposed in exhaust conduit **304**A and may be configured to swirl the cathode exhaust. The anode exhaust conduit **308**D may be fluidly connected to the vortex generator **552** or to the cathode exhaust conduit **304**A or the ATO **500** downstream of the vortex generator **552**. The swirled cathode exhaust may mix with the second portion of the anode exhaust provided by the splitter **550** before being provided to the ATO **500**. The mixture may be oxidized in the ATO **500** to generate an ATO exhaust. The ATO exhaust flows from the ATO **500** to the cathode recuperator **120** through exhaust conduit **304**B. Exhaust flows from the cathode recuperator and out of the hotbox **100** through exhaust conduit **304**C.

(18) Water flows from a water source **206**, such as a water tank or a water pipe, to the water injector **160** through water conduit **306**. The water injector **160** injects water directly into first portion of the anode exhaust provided in conduit **308**C. Heat from the first portion of the anode exhaust (also referred to as a recycled anode exhaust stream) provided in exhaust conduit **308**C 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 provided from the anode exhaust cooler **140** to the mixer **210** through the anode exhaust conduit **308**E. The mixer **210** is configured to mix the steam and first portion of the anode exhaust with fresh fuel (i.e., fuel inlet stream). This humidified fuel mixture may then be heated in the anode recuperator **110** by the anode exhaust, before being provided to the 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 **100**. The reforming catalyst(s) reform the humidified fuel mixture before it is provided to the stack **102**.

(19) The system **10** may further a system controller **225** configured to control various elements of the system **10**. The controller **225** may include a central processing unit configured to execute

stored instructions. For example, the controller **225** may be configured to control fuel and/or air flow through the system **10**, according to fuel composition data.

(20) FIG. **2**A is a sectional view showing components of the hot box **100** of the system **10** of FIG. **1**, and FIG. **2**B shows an enlarged portion of FIG. **2**A. FIG. **2**C is a three dimensional cut-away view of a central column **400** of the system **10**, according to various embodiments of the present disclosure, and FIG. **2**D is a perspective view of an anode hub structure **600** disposed in a hot box base **101** on which the column **400** may be disposed.

(21) Referring to FIGS. **2**A-**2**D, the fuel cell stacks **102** may be disposed around the central column **400** in the hot box **100**. For example, the stacks **102** may be disposed in a ring configuration around the central column **400** and may be positioned on the hot box base **101**. The column **400** may include the anode recuperator **110**, the ATO **500**, and the anode exhaust cooler **140**. In particular, the anode recuperator **110** is disposed radially inward of the ATO **500**, and the anode exhaust cooler **140** is mounted over the anode recuperator **110** and the ATO **500**. In one embodiment, an oxidation catalyst **112** and/or the hydrogenation catalyst **114** may be located in the anode recuperator **110**. A reforming catalyst **116** may also be located at the bottom of the anode recuperator **110** as a steam methane reformation (SMR) insert.

(22) The ATO **500** comprises an outer cylinder **502** that is positioned around inner ATO insulation **556**/outer wall of the anode recuperator **110**. Optionally, the insulation **556** may be enclosed by an ATO inner cylinder **504**. Thus, the insulation **556** may be located between the anode recuperator **110** and the ATO **500**. An ATO oxidation catalyst may be located in the space between the outer cylinder **502** and the ATO insulation **556**. A fuel inlet path bellows **854** may be located between the anode exhaust cooler **140** and the inner ATO cylinder **504**. An ATO thermocouple feed through **1601** extends through the anode exhaust cooler **140**, to the top of the ATO **500**. The temperature of the ATO **500** may thereby be monitored by inserting one or more thermocouples (not shown) through this feed through **1601**.

(23) The anode hub structure **600** may be positioned under the anode recuperator **110** and ATO **500** and over the hot box base **101**. The anode hub structure **600** is covered by an ATO skirt **1603**. The vortex generator **552** and fuel exhaust splitter **550** are located over the anode recuperator **110** and ATO **500** and below the anode exhaust cooler **140**. An ATO glow plug **1602**, which initiates the oxidation of the stack fuel exhaust in the ATO during startup, may be located near the bottom of the ATO **500**.

(24) The anode hub structure **600** is used to distribute fuel evenly from the central column to fuel cell stacks **102** disposed around the central column **400**. The anode flow hub structure **600** includes a grooved cast base **602** and a “spider” hub of fuel inlet conduits **300**D and outlet conduits **308**A. Each pair of conduits **300**D, **308**A connects to a fuel cell stack **102**. Anode side cylinders (e.g., anode recuperator **110** inner and outer cylinders and ATO outer cylinder **502**) are then welded or brazed into the grooves in the base **602**, creating a uniform volume cross section for flow distribution as discussed below.

(25) A lift base **1604** is located under the hot box base **101**, as illustrated in FIG. **2**C. In an embodiment, the lift base **1604** includes two hollow arms with which the forks of a fork lift can be inserted to lift and move the system, such as to remove the system from a cabinet (not shown) for repair or servicing.

(26) As shown by the arrows in FIGS. **2**A and **2**B, air enters the top of the hot box **100** and then flows into the cathode recuperator **120** where it is heated by ATO exhaust (not shown) from the ATO **500**. The heated air then flows inside the cathode recuperator **120** through a first vent or opening **121**. The air then flows through the stacks **102** and reacts with fuel (i.e., fuel inlet stream) provided from the anode hub structure **600**. Air exhaust flows from the stacks **102**, through a second vent or opening **123**. The air exhaust then passes through vanes of the vortex generator **552** and is swirled before entering the ATO **500**.

(27) The splitter **550** may direct the second portion of the fuel exhaust exiting the top of the anode

recuperator **100** through openings (e.g., slits) in the splitter into the swirled air exhaust (e.g., in the vortex generator **552** or downstream of the vortex generator in conduit **304**A or in the ATO **500**). At such the fuel and air exhaust may be mixed before entering the ATO **500**.

(28) FIGS. **3**A and **3**B are side cross-sectional views showing flow distribution through the central column **400**, and **3**C is top cross-sectional view taken through the anode recuperator **110**. Referring to FIGS. **2**A, **2**B, **3**A, and **3**C, the anode recuperator **110** includes an inner cylinder **110**A, a corrugated plate **110**B, and an outer cylinder **110**C that may be coated with the ATO insulation **556**. Fuel from fuel conduit **300**C enters the top of the central column **400**. The fuel then bypasses the anode exhaust cooler **140** by flowing through its hollow core and then flows through the anode recuperator **110**, between the outer cylinder **110**C and the and the corrugated plate **110**B. The fuel then flows through the hub base **602** and conduits **300**D of the anode hub structure **600** shown in FIG. **3**B, to the stacks **102**.

(29) Referring to FIGS. **2**A, **2**B, **2**C, **3**A, and **3**B, the fuel exhaust flows from the stacks **102** through conduits **308**A into the hub base **602**, and from the hub base **602** through the anode recuperator **110**, between in inner cylinder **110**A and the corrugated plate **110**B, and through conduit **308**B into the splitter **550**. The first portion of the fuel exhaust flows from the splitter **550** to the anode exhaust cooler **140** through conduit **308**C, while the second portion flows from the splitter **550** to the ATO **500** through conduit **308**D, as shown in FIG. **1**. Anode exhaust cooler inner core insulation **140**A may be located between the fuel conduit **300**C and bellows **852**/supporting cylinder **852**A located between the anode exhaust cooler **140** and the vortex generator **552**, as shown in FIG. **3**A. This insulation minimizes heat transfer and loss from the first portion of the anode exhaust stream in conduit **308**C on the way to the anode exhaust cooler **140**. Insulation **140**A may also be located between conduit **300**C and the anode exhaust cooler **140** to avoid heat transfer between the fuel inlet stream in conduit **300**C and the streams in the anode exhaust cooler **140**. In other embodiments, insulation **140**A may be omitted from inside the cylindrical anode exhaust cooler **140**.

(30) FIG. **3**B also shows air flowing from the air conduit **302**A to the anode exhaust cooler **140** (where it is heated by the first portion of the anode exhaust) and then from the anode exhaust cooler **140** through conduit **302**B to the cathode recuperator **120**. The first portion of the anode exhaust is cooled in the anode exhaust cooler **140** by the air flowing through the anode exhaust cooler **140**. The cooled first portion of the anode exhaust is then provided from the anode exhaust cooler **140** to the anode recycle blower **212** shown in FIG. **1**.

(31) As will be described in more detail below and as shown in FIGS. **2**A and **3**B, the anode exhaust exits the anode recuperator **110** and is provided into splitter **550** through conduit **308**B. The splitter **550** splits the anode exhaust into first and second anode exhaust portions (i.e., streams). The first stream is provided into the anode exhaust cooler **140** through conduit **308**C. The second stream is provided to the ATO **500** through conduit **308**D.

(32) The relative amounts of anode exhaust provided to the ATO **500** and the anode exhaust cooler **140** is controlled by the anode recycle blower **212**. The higher the blower **212** speed, the larger portion of the anode exhaust is provided into conduit **308**C and a smaller portion of the anode exhaust is provided to the ATO **500** via conduit **308**D, and vice-versa.

(33) The anode exhaust provided to the ATO **500** is not cooled in the anode exhaust cooler **140**. This allows higher temperature anode exhaust to be provided into the ATO **500** than if the anode exhaust were provided after flowing through the anode exhaust cooler **140**. For example, the anode exhaust provided into the ATO **500** from the splitter **550** may have a temperature of above 350° C., such as from about 350 to about 500° C., for example, from about 375 to about 425° C., or from about 390 to about 410° C. Furthermore, since a smaller amount of anode exhaust is provided into the anode exhaust cooler **140** (e.g., not 100% of the anode exhaust is provided into the anode exhaust cooler due to the splitting of the anode exhaust in splitter **550**), the heat exchange area of the anode exhaust cooler **140** may be reduced. The anode exhaust provided to the ATO **500** may be

oxidized by the stack cathode (i.e., air) exhaust and provided to the cathode recuperator **120** through conduit **304**B.

(34) FIG. **4** is a sectional perspective view showing the water injector **160** and ATO **500** in the central column of FIG. **2**A. Referring to FIG. **4**, the splitter **550** comprises the horizontal slits shown in FIG. **3**A. However, in other embodiments, the splitter **550** may comprise tubes that extend through the outer wall of the anode exhaust conduit **308**B rather than the slits.

(35) The water injector **160** may include and injector ring **162** and a shroud **166**. The injector ring **162** may be disposed inside the anode exhaust conduit **308**C between the anode exhaust cooler **140** and the anode recuperator **110** and may be fluidly connected to the water conduit **306**. The injector ring **162** is a tube that extends around the fuel conduit **300**C. The injector ring **162** may include injection apertures (i.e., openings) **162**A configured to inject water directly into the first portion of the anode exhaust flowing in the conduit **308**C from the splitter **550** and anode recuperator **110**. The water may be vaporized by the hot first portion of the anode exhaust. The injection apertures **162**A may be configured to generate streams or droplets of water, which may be vaporized instantaneously or within seconds of emerging from the injector ring **162**. The injector ring **162** may also be sized to provide substantially uniform circumferential flow of water therein and to minimize a pressure drop in the anode exhaust flowing thereby.

(36) The shroud **166** may be a cylinder which surrounds the injector ring **162**. The shroud **166** may be configured to segregate the water from the second portion of the anode exhaust flowing into the ATO **500** through the splitter **550**. In particular, the second portion of the anode exhaust flowing outside of the shroud **166** may be directed by the splitter **550** radially outward toward the anode exhaust conduit **308**D and the ATO **500**, while the first portion of the anode exhaust flowing inside of the shroud **166** is directed upward by the splitter **550** toward the injector ring **162** in the anode exhaust conduit **308**C. Accordingly, the shroud **166** may be configured to prevent or reduce the amount of water and/or the first portion of the anode exhaust that has been humidified by the injected water from being injected into the ATO **500** by the splitter **550**. In other words, the shroud **166** is configured such that substantially all of the water and the humidified first portion of the anode exhaust are directed towards the anode exhaust cooler **140**.

(37) The ATO **500** may surround the anode recuperator **110**, and the catalysts **112**, **114** and **116** may be disposed inside the inner plenum which is surrounded by the anode recuperator **110**, similar to the configuration described in U.S. Pat. No. 9,287,572 B2, issued Mar. 15, 2016 and incorporated herein by reference in its entirety.

(38) The ATO **500** may include a catalyst ring **510** disposed in an annular chamber formed between the outer cylinder **502** and the inner cylinder **504**. In particular, the catalyst ring **510** may be disposed at a distance from the splitter **550** that is sufficient for a majority of the oxidation of fuel exhaust to occur prior to the exhaust entering the catalyst ring **510**. In other words, the distance may be set such that un-catalyzed oxidation of the exhaust, such as the oxidation of hydrogen to form water and/or oxidation of carbon monoxide to form carbon dioxide, may be complete or more than 50% complete, before the exhaust enters the catalyst ring **510**.

(39) The catalyst ring **510** may be configured to catalyze the oxidation of oxidizable species that remain in the catalyst exhaust after the un-catalyzed oxidation. For example, the catalyst ring **510** may include a catalyst or mixture of catalysts configured to catalyze the oxidation of carbon monoxide and/or fuel (e.g., hydrogen or hydrocarbon fuel, such as natural gas or methane) remaining in the exhaust.

(40) FIG. **5**A is a photograph showing an exemplary central column **400**, with the outer cylinder **502** of the ATO **500** removed, FIG. **5**B is a photograph showing a top perspective view of the catalyst ring **510** of the ATO **500**, and FIG. **5**C is a photograph showing a close up view of the top surface of a portion of the catalyst ring **510**, according to various embodiments of the present disclosure.

(41) Referring to FIGS. **5**A-**5**C, the catalyst ring **510** may include an outer wall **512**, an inner wall

514, and a matrix **515** disposed there between. In some embodiments, the catalyst ring **510** may be formed of a high-temperature stable material, such as metals, for example stainless steel or Inconel (i.e., a high temperature nickel based alloy), or ceramic materials such as alumina, or the like. For example, the walls **512** may be metal and the matrix **515** may be ceramic coated with catalyst metal. In some embodiments, the outer wall **512** and the inner wall **514** may be cylindrical when viewed from the top. However other ring shapes, such as rectangular or hexagonal ring shapes may alternatively be used. The outer wall **512** may concentrically surrounding the inner wall **514**. The inner wall **514** may be attached to the inner cylinder **504** of the ATO **500**. The matrix **515** is attached to the inner wall **514** and the outer wall **512** by brazing or another suitable method.

(42) The matrix **515** may have a honeycomb-type structure including channels **516**. The channels **516** may have any shape, so long as the channels **516** are configured to permit a fluid to flow through the catalyst ring **510**, from the top surface to an opposing bottom surface of the catalyst ring **510**. For example, the channels **516** may be straight or curved. In some embodiments, the channels **516** may extend in a direction that is substantially perpendicular to a plane of the top surface and/or bottom surface of the catalyst ring **510**.

(43) In some embodiments, the channels **516** may be arranged in concentric rings surrounding the inner wall **514**. For example, the channels **516** may be arranged in at least 3, such as at least 5, at least 10, or at least 15 concentric rings. In other embodiments, the channels **516** may be disposed in an irregular arrangement. For example, the channels **516** may have any arrangement, so long as at least 3, such as at least 5, at least 10, or at least 15 channels **516** are disposed in a radial (i.e., horizontal) direction A (see FIG. 5C), extending between the outer wall **512** and the inner wall **514**. The radial direction A may be perpendicular to the axial (i.e., vertical) direction of fluid (i.e., fuel and air exhaust) flow through the catalyst ring **510**.

(44) In one embodiment shown in FIG. 5C, the matrix **515** may be formed from concentric cylindrical walls **517** (such as three or more concentric walls **517**) separated from each other by cylindrical corrugated spacers **518**. In some embodiments, the cylindrical walls **517**, spacers **518**, and/or the outer and inner walls **512**, **514** may be attached to one another by, for example, brazing or welding. The channels **516** may have a trapezoidal horizontal cross sectional shape, with the short and long parallel trapezoid sides alternating in the angular (i.e., clockwise or counter-clockwise) direction when viewed from the top.

(45) In an alternative embodiment shown in FIG. 5D, the cylindrical walls **517** may be omitted from the matrix **515**. In this embodiment, the corrugated spacers **518** are attached to each other rather than to the pair of adjacent cylindrical walls **517**. In this embodiment, the channels **516** may have a hexagonal horizontal cross sectional shape direction when viewed from the top. The channels **516** form a close-packed hexagonal array when viewed from the top.

(46) The matrix **515** may be loaded (i.e., having the surfaces of the channels coated) with an oxidation catalyst. In particular, the honeycomb structure of the matrix **515** may provide a high surface area for catalyst loading. Suitable oxidation catalysts may be configured to catalyze the oxidation carbon monoxide into carbon dioxide and/or oxidize any fuel remaining in the exhaust. For example, suitable oxidation catalyst may include catalyst metals such as platinum (Pt), palladium (Pd), rhodium (Rh), iridium (Ir), osmium (Os), ruthenium (Ru), tantalum (Ta), nickel (Ni), copper (Cu), oxides thereof, alloys thereof, combinations thereof, or the like. In some embodiments, the oxidation catalyst may include palladium. The oxidation catalyst may be applied to the matrix **515** using any suitable process, such as by a washcoating process, for example.

(47) FIG. **6** is a schematic view of an alternative ATO **500**A, according to various embodiments of the present disclosure. The ATO **500**A may be similar to the ATO **500**. Accordingly, on the differences there between will be described in detail.

(48) Referring to FIG. **6**, the ATO **500**A may include two or more catalyst rings **510**. For example, the ATO **500**A may include three catalyst rings **510** with the first ring located over the second ring, and the second ring located above the third ring, as shown in FIG. **6**. However, the present

disclosure is not limited to any particular number of catalyst rings **510**. For example, the number of catalyst rings **510** may be selected based on the composition of exhaust the ATO **500**A is configured to receive.
(49) The catalyst rings **510** may be disposed between the outer cylinder **502** and the inner cylinder **504**, such that exhaust flowing through the ATO **500**A, (e.g., between the outer cylinder **502** and the inner cylinder **504**) passes through each catalyst ring **510**. In some embodiments, the catalyst rings **510** may be disposed in a lower portion of the ATO **500**A, in order to permit non-catalyzed oxidation of the exhaust to be substantially complete, before the exhaust enters the catalyst rings **510**. The catalyst rings **510** and may be spaced apart from one another in the axial (i.e. vertical) direction, as shown in FIG. **6**, or may directly contact one another. For example, the catalyst rings **510** may be spaced apart from one another, in an exhaust flow direction as shown by the exhaust flow arrows in FIG. **6**, by a distance ranging from 0 to about 10 cm, such as from 0.5 to 5 cm, or from 1 to 2 cm.
(50) In some embodiments, the catalyst rings **510** may be loaded with the same oxidation catalyst and/or may each have the same amount of catalyst loading. In other embodiments, the catalyst rings **510** may include different catalysts and/or may have different catalyst loading amounts.
(51) The present inventors have determined that an ATO including a catalyst ring, as described herein may provide various unexpected benefits, as compared to conventional ATO designs. For example, the catalyst ring may provide an increased surface area for catalyst loading, which may increase the active area for oxidation, as compared to conventional designs. In addition, the catalyst ring may have a longer service life and may be manufactured at a lower cost, as compared to conventional designs.
(52) 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. An anode tail gas oxidizer (ATO), comprising: an inner ATO wall; an outer ATO wall; and a first catalyst ring disposed in a chamber formed between the inner ATO wall and the outer ATO wall, the first catalyst ring comprising: an inner wall that contacts the inner ATO wall; an outer wall that contacts the outer ATO wall; and a matrix that extends from the inner wall to the outer wall, the matrix comprising channels that are loaded with an oxidation catalyst and that extend from a top surface to an opposing bottom surface of the first catalyst ring.
2. The ATO of claim 1, wherein: the ATO is configured to provide fluid flow through the chamber in an axial direction; and the channels extend lengthwise in the axial direction.
3. The ATO of claim 1, wherein the matrix comprises: concentric cylindrical walls; and cylindrical corrugated spacers disposed between the walls.
4. The ATO of claim 3, wherein the cylindrical walls and the spacers are brazed to each other to form the matrix.
5. The ATO of claim 3, wherein the matrix comprises at least three of the concentric cylindrical walls which are separated by the cylindrical corrugated spacers.
6. The ATO of claim 3, wherein the channels are at least partially defined by the walls and the spacers.
7. The ATO of claim 6, wherein the channels have a trapezoidal horizontal cross sectional shape, with the short and long parallel trapezoid sides alternating in an angular direction.
8. The ATO of claim 1, wherein the channels have a hexagonal horizontal cross sectional shape.

9. The ATO of claim 1, wherein the matrix comprises at least ten of the channels in a radial direction perpendicular to an axial direction of fluid flow through the first catalyst ring.
10. The ATO of claim 1, wherein the matrix comprises alumina.
11. An anode tail gas oxidizer (ATO), comprising: an inner ATO wall; an outer ATO wall; a first catalyst ring disposed in a chamber formed between the inner ATO wall and the outer ATO wall, the first catalyst ring comprising: an inner wall; an outer wall; and a matrix disposed between the inner wall and the outer wall and loaded with an oxidation catalyst; and a second catalyst ring disposed in the chamber below the first catalyst ring, the second catalyst ring comprising: an inner wall; an outer wall; and a matrix disposed between the inner wall and the outer wall and loaded with an oxidation catalyst.
12. The ATO of claim 11, wherein the first and second catalyst ring directly contact each other or are spaced apart within the chamber.
13. The ATO of claim 11, further comprising a third catalyst ring disposed in the chamber below the second catalyst ring, the third catalyst ring comprising: an inner wall; an outer wall; and a matrix disposed between the inner wall and the outer wall and loaded with an oxidation catalyst.
14. A fuel cell system comprising: fuel cell stacks; a central column; and the ATO of claim 1 located between the fuel cell stacks and the central column.
15. The fuel cell system of claim 14, wherein: the ATO is cylindrical and surrounds the central column; and the fuel cell stacks surround the ATO.
16. The fuel cell system of claim 15, wherein the central column comprises: an anode recuperator configured to heat fuel provided to the fuel cell stacks using anode exhaust output from the fuel cell stacks; and an anode exhaust cooler configured to heat air provided to the fuel cell stacks using the anode exhaust output from and the anode recuperator.
17. The fuel cell system of claim 16, further comprising a splitter configured to provide a first portion of the anode exhaust output from the anode recuperator to the ATO, and to provide a second portion of the anode exhaust output from the anode recuperator to the anode exhaust cooler.
18. The fuel cell system of claim 17, further comprising a vortex generator containing vanes located above the splitter and configured to swirl cathode exhaust output from the fuel cell stacks into the first portion of the anode exhaust flowing from the splitter through the chamber toward the first catalyst ring.
19. The fuel cell system of claim 17, wherein the ATO surrounds the anode recuperator.
20. The fuel cell system of claim 17, wherein: the cathode exhaust oxidizes a majority of the first portion of the anode exhaust in the chamber before the anode exhaust enters the first catalyst ring; and the first catalyst ring is configured to oxidize a remaining part of the first portion of the anode exhaust.
21. A fuel cell system comprising: fuel cell stacks; a central column comprising an anode recuperator configured to heat fuel provided to the fuel cell stacks using anode exhaust output from the fuel cell stacks, and an anode exhaust cooler disposed configured to heat air provided to the fuel cell stacks using the anode exhaust output from and the anode recuperator; an anode tail gas oxidizer (ATO), located between the fuel cell stacks and the central column; a splitter configured to provide a first portion of the anode exhaust output from the anode recuperator to the ATO, and to provide a second portion of the anode exhaust output from the anode recuperator to the anode exhaust cooler; and a vortex generator containing vanes located above the splitter; wherein: the ATO comprises: an inner ATO wall; an outer ATO wall; a first catalyst ring disposed in a chamber formed between the inner ATO wall and the outer ATO wall, the first catalyst ring comprising: an inner wall; an outer wall; and a matrix disposed between the inner wall and the outer wall and loaded with an oxidation catalyst; and the vortex generator is configured to swirl cathode exhaust output from the fuel cell stacks into the first portion of the anode exhaust flowing from the splitter through the chamber toward the first catalyst ring.