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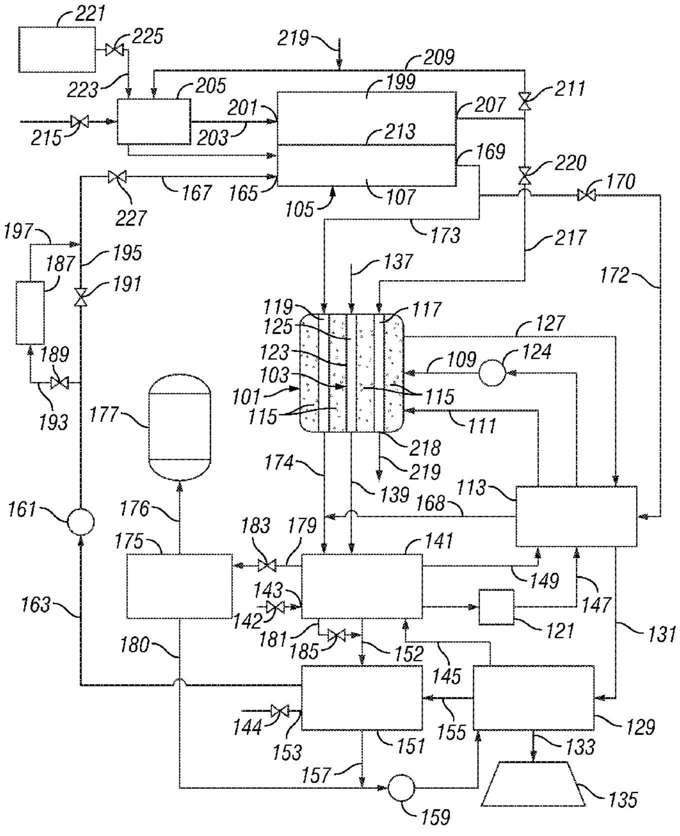

FIG. 1

(57) Abstract: The present invention is directed to a solid oxide fuel cell system for generating electrical power. The system comprises a solid oxide fuel cell, a reforming reactor, a hydrogen separation apparatus, and an anode exhaust conduit. The reforming reactor includes a reforming region in which a feed comprising one or more hydrocarbons may be steam reformed to produce a reformed product gas containing hydrogen. The hydrogen separation apparatus is located in the reforming reactor positioned to separate hydrogen from the reformed product gas produced in the reforming reactor. The hydrogen separation apparatus is operatively connected to the anode of the solid oxide fuel cell to provide hydrogen to the fuel cell as a fuel to be oxidized to produce electricity. The anode exhaust conduit is located in the reforming region of the reforming reactor and is operatively connected to the anode exhaust of the fuel cell so that hot anode exhaust exiting the fuel cell may pass through the anode exhaust conduit and exchange heat with reactants in the reforming region of the reforming reactor.

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FUEL CELL-BASED PROCESS FOR GENERATING ELECTRICAL POWER

Field of the Invention

The present invention relates to electrical power generating fuel cell systems, and to a process for generating electrical power. In particular, the present invention relates to an electrical power generating solid oxide fuel cell system and a process for generating electrical power with such a system.

Background of the Invention

Solid oxide fuel cells are fuel cells that are composed of solid-state elements that generate electrical power directly from an electrochemical reaction. Such fuel cells are useful in that they deliver high quality reliable electrical power, are clean operating, and are relatively compact power generators-making their use attractive in urban areas.

Solid oxide fuel cells are formed of an anode, a cathode, and a solid electrolyte sandwiched between the anode and cathode. An oxidizable fuel gas, or a gas that may be reformed in the fuel cell to an oxidizable fuel gas, is fed to the anode, and an oxygen containing gas, typically air, is fed to the cathode to provide the chemical reactants. The oxidizable fuel gas fed to the anode is typically syngas-a mixture of hydrogen and carbon monoxide. The fuel cell is operated at a high temperature, typically from 800°C to 1100°C, to convert oxygen in the oxygen containing gas to ionic oxygen that may cross the electrolyte to interact with hydrogen and/or carbon monoxide from the fuel gas at the anode. Electrical power is generated by the conversion of oxygen to ionic oxygen at the cathode and the chemical reaction of the ionic oxygen with hydrogen and/or carbon monoxide at the anode. The following reactions describe the electrical power generating chemical reactions in the cell:

Cathode charge transfer: $O_2 + 4e^- \rightarrow 2O^=$

Anode charge transfer: $H_2 + O^= \rightarrow H_2O + 2e^-$ and

$CO + O^= \rightarrow CO_2 + 2e^-$

An electrical load or storage device may be connected between the anode and the cathode so an electrical current may flow between the anode and cathode, powering the electrical load or providing electrical power to the storage device.

Fuel gas is typically supplied to the anode by a steam reforming reactor that reforms a low molecular weight hydrocarbon and steam into hydrogen and carbon oxides. Methane, for example as natural gas, is a preferred low molecular weight hydrocarbon used to produce fuel gas for the fuel cell. Alternatively, the fuel cell anode may be designed to internally effect a steam reforming reaction on a low molecular weight hydrocarbon such as methane and steam supplied to the anode of the fuel cell.

Methane steam reforming provides a fuel gas containing hydrogen and carbon monoxide according to the following reaction: $CH_4 + H_2O \rightleftarrows CO + 3H_2$. Heat must be supplied to effect the steam reforming reaction since the reaction to form hydrogen and carbon monoxide is quite endothermic. The reaction is typically conducted at a temperature in the range of 750°C to 1100°C to convert a substantial amount of methane or other hydrocarbon and steam to hydrogen and carbon monoxide.

Heat for inducing the methane steam reforming reaction in a steam reforming reactor has been conventionally provided by a burner that combusts an oxygen containing gas with a fuel, typically a hydrocarbon fuel such as natural gas, to provide the required heat. Flameless combustion has also been utilized to provide the heat for driving the steam reforming reaction, where the flameless combustion is also driven by providing a hydrocarbon fuel and a oxygen containing gas to a flameless combustor in relative amounts that avoid inducing flammable combustion. These methods for providing the heat necessary to drive a steam reforming reaction are relatively inefficient energetically since a significant amount of thermal energy provided by combustion is not captured and is lost.

U.S. Patent No. 4,128,700 discloses a system and a process thermally integrating a steam reforming reactor and a fuel cell, where the fuel cell provides heat to drive the reforming reactor and the reforming reactor provides a fuel gas for the fuel cell. The steam reforming reactor is heated by burning exhaust from a fuel cell anode, mostly unreacted hydrogen and water, to drive the reforming reaction and to produce reformed products including hydrogen and carbon monoxide. The reformed products are fed to the fuel cell for electrochemical reaction in the fuel cell. The hot burner gases formed by burning the fuel cell anode exhaust are of sufficiently high temperature to provide the heat to drive the 750°C-1100°C steam reforming reaction in the reforming reactor. The system thermally integrates the operation of the reforming reactor and the fuel cell, however, the thermal integration is relatively inefficient since 1) a great deal of thermal energy provided by burning the fuel cell exhaust is not captured and is lost; and 2) hydrogen is a very expensive fuel for use to drive a burner.

U.S. Patent Application No. 2005/0164051 discloses a system and a process in which a reforming reactor may be thermally integrated with a fuel cell, where heat produced by the fuel cell is used to provide heat to drive the endothermic reaction of the reforming reactor. The reforming reactor is thermally integrated with the fuel cell by placing the reforming reactor in the same hot box as the fuel cell and/or by placing the fuel cell and the reformer in thermal contact with each other. The fuel cell and the reformer may be placed in thermal contact with each other by placing the reformer in close proximity to the fuel cell, where the cathode exhaust conduit of the fuel cell may be in direct contact with the reformer (e.g. by wrapping the cathode exhaust conduit around the reformer, or by one or more walls of the reformer comprising a wall of the cathode exhaust conduit) so that the cathode exhaust from the fuel cell provides conductive heat transfer to the reformer. Supplemental heat is provided from a combustor to the reformer, where the thermal contact of the fuel cell and the reformer lowers the combustion heat requirement of the reformer to effect the reforming reaction (*see, e.g.,* paragraph 0085 of the application). While more efficient than capture of thermal energy from combustion, the process is still relatively inefficient since 1) the heat from the fuel cell is insufficient to completely drive the reforming reaction since the heat of the exhaust from the fuel cell has a temperature at or near the temperature required to drive the reforming reaction (750°C-1100°C), and, unless near perfect heat exchange occurs, the heat from the fuel cell will not be sufficient to drive the reforming reaction without additional heat from another source such as a combustor; and 2) significant amounts of heat from the fuel cell exhaust will be convectively transferred away from the reforming reactor as well as towards the reactor.

Furthermore, solid oxide fuel cells coupled with reforming reactors are typically run in a manner that is not electrochemically efficient and does not produce a high electrical power density. Solid oxide fuel cells are typically operated commercially in a "hydrogen-lean" mode, where the conditions of the production of the fuel gas, for example by steam reforming, are selected to limit the amount of hydrogen exiting the fuel cell in the fuel gas. This is done to balance the electrical energy potential of the hydrogen in the fuel gas with the thermal energy lost by hydrogen leaving the cell without being converted to electrical energy.

Fuel gases containing non-hydrogen compounds, such as carbon monoxide or carbon dioxide, however, are less efficient for producing electrical power in a solid oxide fuel cell than more pure hydrogen fuel gas streams. At a given temperature the electrical power that may be generated in a solid oxide fuel cell increases with increasing hydrogen concentration. This is due to the electrochemical oxidation potential of molecular hydrogen relative to other compounds. For example, molecular hydrogen can produce an electrical power density of 1.3 W/cm^2 at 0.7 volts while carbon monoxide can produce an electrical power density of only 0.5 W/cm^2 at 0.7 volts. Therefore, fuel gas streams containing significant amounts of non-hydrogen compounds are not as efficient in producing electrical power in a solid oxide fuel cell as fuel gases containing mostly hydrogen.

Certain measures have been taken to recapture the energy of excess hydrogen exiting the fuel cell, however, these are significantly less energy efficient than if the hydrogen were electrochemically reacted in the fuel cell. For example, the anode exhaust produced by reacting the fuel gas electrochemically in the fuel cell has been combusted to drive a turbine expander to produce electricity. This, however, is significantly less efficient than capturing the electrochemical potential of the hydrogen in the fuel cell since much of the thermal energy is lost rather than converted by the expander to electrical energy. Fuel gas exiting the fuel cell also has been combusted to provide thermal energy for a variety of heat exchange applications, including driving the reforming reactor as noted above. Almost 50% of the thermal energy provided by combustion, however, is not captured and is lost. Hydrogen is a very expensive gas to use to fire a burner, therefore, conventionally, the amount of hydrogen used in the solid oxide fuel cell is adjusted to utilize most of the hydrogen provided to the fuel cell to produce electrical power and minimize the amount of hydrogen exiting the fuel cell in the fuel cell exhaust.

U.S. Patent Application Publication No. 2007/0017369 (the '369 publication) provides a method of operating a fuel cell system in which a feed is provided to a fuel inlet of the fuel cell. The feed may include a mixture of hydrogen and carbon monoxide provided from an external steam reformer or, alternatively may include a hydrocarbon feed that is reformed to hydrogen and carbon monoxide internally in the fuel cell stack. The fuel cell stack is operated to generate electricity and a fuel exhaust stream that contains hydrogen and carbon monoxide, where the hydrogen and carbon monoxide in the fuel exhaust stream are separated from the fuel exhaust stream and fed back to the fuel inlet as a portion of the feed. The fuel gas for the fuel cell, therefore, is a mixture of hydrogen and carbon monoxide derived by reforming a hydrocarbon fuel source and hydrogen and carbon monoxide separated from the fuel exhaust system. Recycling at least a portion of the hydrogen from the fuel exhaust through the fuel cell enables a high operation efficiency to be achieved. The system further provides high fuel utilization in the fuel cell by utilizing about 75% of the fuel during each pass through the stack.

U.S Patent Application Publication No. 2005/0164051 provides a method of operating a fuel cell system in which a fuel is provided to a fuel inlet of the fuel cell. The fuel may be a hydrocarbon fuel such as methane; natural gas containing methane with hydrogen and other gases; propane; biogas; an unreformed hydrocarbon fuel mixed with a hydrogen fuel from a reformer; or a mixture of a non-hydrocarbon carbon containing gas such as carbon monoxide, carbon dioxide, oxygenated carbon containing gas such as methanol, or other carbon containing gas with a hydrogen containing gas such as water vapor or syngas. The fuel cell stack is operated to generate electricity and a fuel exhaust stream that contains hydrogen. A hydrogen separator is utilized to separate non-utilized hydrogen from the fuel side exhaust stream of the fuel cell. The hydrogen separated by the hydrogen separator may be re-circulated back to the fuel cell or may be directed to a subsystem for other uses having a hydrogen demand. The amount of hydrogen re-circulated back to the fuel cell may be selected according to electrical demand or hydrogen demand, where more hydrogen is re-circulated back to the fuel cell when electrical demand is high. The fuel cell stack may be operated at a fuel utilization rate of from 0 to 100%, depending on electrical demand. When the electrical demand is high, the fuel cell is operated at a high fuel utilization rate to increase electricity production—a preferred rate is from 50 to 80%.

Further improvement in the thermal efficiency and electrical efficiency to increase electrical power density in reforming reactor-solid oxide fuel cell systems and processes for operating such systems is desirable.

Summary of the Invention

In one aspect, the present invention is directed to a system for generating electricity, comprising:

a) a solid oxide fuel cell comprising
    1) an anode having
        (i) an anode inlet; and
        (ii) an anode exhaust outlet
    2) a cathode having
        (i) a cathode inlet; and
        (ii) a cathode exhaust outlet; and

3) an electrolyte positioned between, contacting, and separating the anode and the cathode;

b) a reforming reactor comprising

1) a reforming region adapted to reform a vaporized mixture of steam and a feed comprising one or more gaseous hydrocarbons, said reforming region containing a reforming catalyst bed with at least one reforming catalyst therein positioned to contact the vaporized mixture of steam and feed in the reforming region; and

2) one or more reforming region inlets coupled in gaseous communication with the reforming region through which steam, a feed comprising one or more gaseous hydrocarbons, or a vaporized mixture of steam and a feed comprising one or more gaseous hydrocarbons may be introduced to the reforming region;

c) a hydrogen separation apparatus having

1) a member selectively permeable to hydrogen located in the reforming region of the reforming reactor and in gaseous communication with the reforming region of the reforming reactor; and

2) a hydrogen gas outlet operatively coupled in gaseous communication with the member, the member being interposed between the reforming region of the reforming reactor and the hydrogen gas outlet to permit selective flow of hydrogen from the reforming region to the hydrogen gas outlet through the member, wherein the hydrogen gas outlet is operatively coupled in gaseous communication with the anode inlet of the fuel cell;

d) an anode exhaust conduit operatively coupled in gaseous communication with the anode exhaust outlet, at least a portion of the anode exhaust conduit being located in the reforming region of the reforming reactor, the anode exhaust conduit being positioned within the reforming region of the reforming reactor in thermal communication with the reforming region effective to exchange heat from a hot gas exiting the anode of the solid oxide fuel cell with the catalyst in the reforming region and any steam and feed present in the reforming region.

In another aspect, the present invention is directed to a system for generating electricity, comprising:

a) a solid oxide fuel cell comprising

    1) an anode having

        (i) an anode inlet; and

        (ii) an anode exhaust outlet

    2) a cathode having

        (i) a cathode inlet; and

        (ii) a cathode exhaust outlet; and

    3) an electrolyte positioned between, contacting, and separating the anode and the cathode;

b) a reforming reactor comprising

    1) a reforming region adapted to reform a vaporized mixture of steam and a feed comprising one or more gaseous hydrocarbons, said reforming region containing a reforming catalyst bed with at least one reforming catalyst therein positioned to contact the vaporized mixture of steam and feed in the reforming region; and

    2) one or more reforming region inlets coupled in gaseous communication with the reforming region through which steam, a feed comprising one or more gaseous hydrocarbons, or a vaporized mixture of steam and a feed comprising one or more gaseous hydrocarbons may be introduced to the reforming region;

c) a hydrogen separation apparatus having

    1) a member selectively permeable to hydrogen located in the reforming region of the reforming reactor and in gaseous communication with the reforming region of the reforming reactor; and

    2) a hydrogen gas outlet operatively coupled in gaseous communication with the member, the member being interposed between the reforming region of the reforming reactor and the hydrogen gas outlet to permit selective flow of hydrogen from the reforming region to the hydrogen gas outlet through the member, wherein the hydrogen gas outlet is operatively coupled in gaseous communication with the anode inlet of the fuel cell;

d) an cathode exhaust conduit operatively coupled in gaseous communication with the cathode exhaust outlet, at least a portion of the cathode exhaust conduit being located in the reforming region of the reforming reactor, the cathode exhaust conduit being positioned within the reforming region of the reforming reactor in thermal communication with the reforming region effective to exchange heat from a hot gas exiting the cathode of the solid oxide fuel cell with the catalyst in the reforming region and any steam and feed present in the reforming region.

In yet another aspect, the present invention is directed to a system for generating electricity, comprising:

a) a solid oxide fuel cell comprising
    1) an anode having
        (i) an anode inlet
        (ii) an anode exhaust outlet
    2) a cathode having
        (i) a cathode inlet; and
        (ii) a cathode exhaust outlet; and
    3) an electrolyte positioned between, contacting, and separating the anode and the cathode;
b) a reforming reactor comprising
    1) a reforming region adapted to reform a vaporized mixture of steam and a feed comprising one or more gaseous hydrocarbons, said reforming region containing a reforming catalyst bed with at least one reforming catalyst therein positioned to contact the vaporized mixture of steam and feed in the reforming region; and
    2) one or more reforming region inlets coupled in gaseous communication with the reforming region through which steam, a feed comprising one or more gaseous hydrocarbons, or a vaporized mixture of steam and a feed comprising one or more gaseous hydrocarbons may be introduced to the reforming region;
c) a hydrogen separation apparatus having
    1) a member selectively permeable to hydrogen operatively coupled in gaseous communication with the reforming region of the reforming reactor; and
    2) a hydrogen gas outlet operatively coupled in gaseous communication

with the member, the member being interposed between the reforming region of the reforming reactor and the hydrogen gas outlet to permit selective flow of hydrogen from the reforming region to the hydrogen gas outlet through the member, wherein the hydrogen gas outlet is operatively coupled in gaseous communication with the anode inlet of the fuel cell;

d) an anode exhaust conduit operatively coupled in gaseous communication with the anode exhaust outlet, at least a portion of the anode exhaust conduit being located in the reforming region of the reforming reactor, the anode exhaust conduit being positioned within the reforming region of the reforming reactor in thermal communication with the reforming region effective to exchange heat from a hot gas exiting the anode of the solid oxide fuel cell with the catalyst in the reforming region and any steam and feed present in the reforming region.

Brief Description of the Drawings

Fig. 1 is a schematic of a system of the present invention for conducting a process of the present invention in which a reforming reactor is operatively connected to and thermally integrated with a solid oxide fuel cell.

Fig. 2 is a schematic of a system of the present invention for conducting a process of the present invention in which a pre-reforming reactor and a reforming reactor are operatively connected to and thermally integrated with a solid oxide fuel cell.

Fig. 3 is a schematic of a part of a system invention for conducting a process of the present invention in which a hydrogen separation device is operatively connected to a reforming reactor.

Fig. 4 is a schematic drawing of a basic system of the present invention for producing electricity in accordance with a process of the present invention.

Fig. 5 is a schematic drawing of a basic system of the present invention for producing electricity in accordance with a process of the present invention in which a hydrogen separation apparatus is located exterior of a reforming reactor.

Detailed Description of the Invention

The present invention provides a highly efficient system and process for generating electricity at a high electrical power density in a system utilizing a solid oxide fuel cell. First, the system and process of the present invention are more thermally energetically efficient than systems and processes disclosed in the art, transferring thermal energy from a fuel cell exhaust directly into a reforming reactor, where the reforming reactor is designed to produce hydrogen at much lower temperatures than typical reforming reactors so the heat from the anode exhaust of the fuel cell is sufficiently hot enough to drive the lower temperature reforming reactions with no extraneous heat source. Second, the system and process of the present invention produce a higher electrical power density in a solid oxide fuel cell system than systems and processes disclosed in the art by utilizing a hydrogen-rich fuel and minimizing rather than maximizing the per pass fuel utilization rate of the fuel cell, which is achieved by separating and recycling hydrogen captured from the fuel exhaust of the fuel cell and feeding the hydrogen from a feed and the recycle stream at selected rates to minimize the per pass fuel utilization rate.

In the process of the present invention, heat from the anode exhaust of the fuel cell and, optionally, the cathode exhaust, is directed into the reforming reactor through an anode exhaust conduit and, optionally, through a cathode exhaust conduit, respectively, located within the reforming reactor. Heat from the anode exhaust and, optionally, the cathode exhaust, may be transferred by heat exchange to hydrocarbon and steam reactants, and the reforming catalyst, *within* the reforming reactor to drive the reaction of the reactants to produce hydrogen. Transfer of the heat from the exhaust streams from the fuel cell to the reforming reactor within the reforming reactor permits efficient heat exchange with little loss of thermal energy outside the reactor.

In the process of the invention, the reforming reactions may be effected at a lower temperature than typical reforming reactions since hydrogen is removed from the reaction products, driving the reforming equilibrium towards the formation of hydrogen and permitting the reforming reaction temperature to be lowered. As a result, the temperature of the fuel cell exhaust(s) exchanging heat with the reformer reactants is significantly higher than the temperature required to effect the reforming reaction, so the heat provided by the fuel cell exhaust(s) is sufficient to drive the reforming reactions without any additional heat source. Further, more hydrogen may be produced at the lower reforming reactor temperatures since the equilibrium of the water-gas shift reaction $H_2O + CO \rightleftarrows CO_2 + H_2$ favors the production of hydrogen at the lower reforming reactor temperatures, whereas it is not favored at conventional reforming reaction temperatures.

In the process of the present invention the anode of a solid oxide fuel cell is flooded with hydrogen over the entire path length of the anode so that the concentration of hydrogen at the anode electrode available for electrochemical reaction is maintained at a high level over the entire anode path length, thereby maximizing the electrical power density of the fuel cell. Use of a hydrogen-rich fuel that is primarily, and preferably almost all, hydrogen in the process maximizes the electrical power density of the fuel cell system since hydrogen has a significantly greater electrochemical potential than other oxidizable compounds typically used in solid oxide fuel cell systems such as carbon monoxide.

The process of the present invention also maximizes the electrical power density of the fuel cell system by minimizing, rather than maximizing, the per pass fuel utilization rate of the fuel in the solid oxide fuel cell. The per pass fuel utilization rate is minimized to reduce the concentration of oxidation products, particularly water, throughout the anode path length of the fuel cell so that a high hydrogen concentration is maintained throughout the anode path length. A high electrical power density is provided by the fuel cell since an excess of hydrogen is present for electrochemical reaction at the anode electrode along the entire anode path length of the fuel cell. In a process directed to achieving a high per pass fuel utilization rate, for example greater than 60% fuel utilization, the concentration of oxidation products may exceed the concentration of hydrogen along the anode path length before the fuel has traveled even halfway through the fuel cell, and may be hundreds to thousands of times greater than the concentration of hydrogen in the fuel cell exhaust so that the electrical power provided along the anode path near the fuel inlet of the fuel cell is far greater than the electrical power provided near the anode exhaust.

The process of the present invention is also highly efficient since hydrogen not utilized to produce electricity in the fuel cell is separated from the anode exhaust of the fuel cell and recycled continuously back to the fuel cell. This enables production of a high electrical power density relative to the lowest heating value of the fuel by eliminating the problem associated with losing thermal energy by hydrogen leaving the cell without being converted to electrical energy.

In the system of the present invention, an anode exhaust conduit and/or a cathode exhaust conduit are located in a reforming reactor, and through which heat may be transferred to the reforming reactor to drive reforming reactions in the reactor. An anode exhaust conduit may be coupled to an anode exhaust of the fuel cell so that hot anode exhaust gases from the fuel cell may be directed through the anode exhaust conduit in the reforming reactor to provide thermal energy to drive the reforming reactions in the reforming reactor. Likewise, a cathode exhaust conduit may be coupled to a cathode exhaust of the fuel cell so that hot cathode exhaust gases from the fuel cell may be directed through the cathode exhaust conduit in the reforming reactor to drive the reforming reactions in the reforming reactor.

In the system of the present invention, a hydrogen separation apparatus may separate hydrogen from reformed product gases produced by the reforming reactor. The hydrogen separation apparatus is coupled to the anode inlet of the fuel cell so that a hydrogen rich fuel may be provided to the fuel cell. The anode exhaust may be recycled back to the anode inlet to provide further hydrogen so the system is very electrochemically efficient.

As used herein, the term "hydrogen" refers to molecular hydrogen unless specified otherwise.

As used herein, the "amount of water formed in the fuel cell per unit time of measurement" is calculated as follows: Amount of Water Formed in Fuel Cell per Unit Time of Measurement = [Amount of Water Measured Exiting the Fuel Cell in the Anode Exhaust of the Fuel Cell Per Unit of Time of Measurement] – [Amount of Water Present in the Fuel Fed to the Anode of the Fuel Cell Per Unit of Time of Measurement]. For example, if measurements of the amount of water in a fuel fed to the anode of a fuel cell and exiting the fuel cell in the anode exhaust are taken for 2 minutes, where the measured amount of water in the fuel fed to the anode is 6 moles and the measured amount of water exiting the fuel cell in the anode exhaust is 24 moles, the amount of water formed in the fuel cell as calculated herein is (24 moles/2 minutes) – (6 moles/2 minutes) = 12 moles/min – 3 moles/min = 9 moles/min.

As used herein, when two or more elements are described as "operatively connected" or "operatively coupled", the elements are defined to be directly or indirectly connected or coupled to allow direct or indirect fluid flow between the elements. The term "fluid flow", as used herein, refers to the flow of a gas or a fluid. When two or more elements are described as "selectively operatively connected" or "selectively operatively coupled", the elements are defined to be directly or indirectly connected or coupled to allow direct or indirect fluid flow of a selected gas or fluid between the elements. As used in this definition, "indirect fluid flow" means that a physical characteristic, such as the temperature or the pressure of a gas or a fluid, and/or the composition of a selected gas or fluid may be changed between selected elements by or in one or more additional elements. "Indirect fluid flow" as used in this definition excludes changing the composition of the gas or fluid between the elements by chemical reaction, for example, oxidation or reduction of one or more elements of the fluid or gas.

As used herein, the term "selectively permeable to hydrogen" is defined as permeable to molecular hydrogen or elemental hydrogen and impermeable to other elements or compounds such that at most 10%, or at most 5%, or at most 1% of the non-hydrogen elements or compounds may permeate what is permeable to the molecular or elemental hydrogen.

As used herein, the term "high temperature hydrogen-separation device" is defined as a device or apparatus effective for separating hydrogen, in molecular or elemental form, from a gas stream at a temperature of at least 250°C, typically at temperatures of from 300°C to 650°C.

As used herein, "per pass hydrogen utilization" as referring to the utilization of hydrogen in a fuel in a solid oxide fuel cell, is defined as the amount of hydrogen in a fuel utilized to generate electricity in one pass through the solid oxide fuel cell relative to the total amount of hydrogen in a fuel input into the fuel cell for that pass. The per pass hydrogen utilization may be calculated by measuring the amount of hydrogen in a fuel fed to the anode of a fuel cell, measuring the amount of hydrogen in the anode exhaust of the fuel cell, subtracting the measured amount of hydrogen in the anode exhaust of the fuel cell from the measured amount of hydrogen in the fuel fed to the fuel cell to determine the amount of hydrogen used in the fuel cell, and dividing the calculated amount of hydrogen used in the fuel cell by the measured amount of hydrogen in the fuel fed to the fuel cell. The per pass hydrogen utilization may be expressed as a percent by multiplying the calculated per pass hydrogen utilization by 100.

As used herein, the term "reforming reactor" refers to a reactor in which a hydrocarbon reforming reaction and, optionally, other reactions such as a water-gas shift reaction, may take place. Reactions that occur in a reforming reactor, as used herein, may be predominantly hydrocarbon reforming reactions, but need not be predominantly hydrocarbon reforming reactions. For example, a majority of reactions occurring in a "reforming reactor" may actually be shift reactions in certain instances rather than hydrocarbon reforming reactions.

In an embodiment, the process of the present invention utilizes a system including a thermally integrated hydrogen-separating steam reforming reactor and a solid oxide fuel cell to generate electrical power. Referring to Fig. 1, a steam reforming reactor **101** including one or more high temperature hydrogen-separating membranes **103** is operatively coupled to a solid oxide fuel cell **105** to provide a first gas stream containing primarily hydrogen to the anode **107** of the fuel cell **105**, while the exhaust from the fuel cell **105** provides the heat to the reforming reactor **101** necessary to drive the reforming and shift reactions in the reactor **101**.

In an embodiment of the process, a feed comprising a hydrogen source that is a gaseous hydrocarbon at a temperature of at most 300°C may be fed to the reformer **101** via line **109**. Any (optionally oxygenated) hydrocarbon that is vaporized at a temperature of at most 300°C at a pressure up to 5 MPa may be used in this embodiment of the process as the feed. Such feeds may include, but are not limited to, methane, methanol, ethane, ethanol, propane, butane, and light hydrocarbons having 1-4 carbon atoms in each molecule. In a preferred embodiment, the feed may be methane or natural gas. Steam may be fed to the reformer **101** via line **111** to be mixed with the feed in a reforming region **115** of the reformer **101**.

The feed and the steam may be fed to the reformer **101** at a temperature of from 300°C to 650°C, where the feed and steam may be heated to the desired temperature in heat exchanger **113** as described below. The feed may be desulfurized in a desulfurizer **121** prior to being heated in the heat exchanger **113**, or optionally after being heated in the heat exchanger **113**, but before being fed to the reforming reactor **101**, to remove sulfur from the feed so the feed does not poison any catalyst in the reforming reactor **101**. The feed may be desulfurized in the desulfurizer **121** by contact with a conventional hydrodesulfurizing catalyst.

The feed and steam are fed into a reforming region **115** in the reforming reactor **101**. The reforming region **115** may, and preferably does, contain a reforming catalyst therein. The reforming catalyst may be a conventional steam reforming catalyst, and may be any known in the art. Typical steam reforming catalysts which can be used include, but are not limited to, Group VIII transition metals, particularly nickel. It is often desirable to support the reforming catalysts on a refractory substrate (or support). The support, if used, is preferably an inert compound. Suitable inert compounds for use as a support contain elements of Group III and IV of the Periodic Table, such as, for example the oxides or carbides of Al, Si, Ti, Mg, Ce and Zr.

The feed and steam are mixed and contacted with the reforming catalyst in the reforming region **115** at a temperature effective to form a reformed product gas containing hydrogen and carbon oxides. The reformed product gas may include compounds formed by steam reforming the hydrocarbons in the feed. The reformed product gas may also include compounds formed by shift reacting carbon monoxide produced by steam reforming with additional steam. The reformed product gas may contain hydrogen and at least one carbon oxide. Carbon oxides that may be in the reformed product gas include carbon monoxide and carbon dioxide.

One or more high temperature tubular hydrogen-separation membranes **103** may be located in the reforming region **115** of the reforming reactor **101** positioned so the reformed product gas may contact the hydrogen-separation membrane(s) **103** and hydrogen may pass through the membrane wall member **123** to a hydrogen conduit **125** located within the tubular membrane **103**. The membrane wall member **123** separates the hydrogen conduit **125** from gaseous communication with non-hydrogen compounds of reformed product gas, feed, and steam in the reforming region **115**, and is selectively permeable to hydrogen, elemental and/or molecular, so that hydrogen in the reformed product gas may pass through the membrane wall member **123** to the hydrogen conduit **125** while other gases in the reforming region are prevented by the membrane wall member **123** from passing to the hydrogen conduit **125**.

The high temperature tubular hydrogen-separation membrane(s) **103** in the reforming region may comprise a support coated with a thin layer of a metal or alloy that is selectively permeable to hydrogen. The support may be formed of a ceramic or metallic material that is porous to hydrogen. Porous stainless steel or porous alumina are preferred materials for the support of the membrane **103.** The hydrogen selective metal or alloy coated on the support may be selected from metals of Group VIII, including, but not limited to Pd, Pt, Ni, Ag, Ta, V, Y, Nb, Ce, In, Ho, La, Au, and Ru, particularly in the form of alloys. Palladium and platinum alloys are preferred. A particularly preferred membrane **103** used in the present process has a very thin film of a palladium alloy having a high surface area coating a porous stainless steel support. Membranes of this type can be prepared using the methods disclosed in U.S. Pat. No. 6,152,987. Thin films of platinum or platinum alloys having a high surface area would also be suitable as the hydrogen selective material.

The pressure within the reforming region **115** of the reforming reactor **101** is maintained at a level significantly above the pressure within the hydrogen conduit **125** of the tubular membrane **103** so that hydrogen is forced through the membrane wall member

123 from the reforming region **115** of the reforming reactor into the hydrogen conduit **125**. In an embodiment, the hydrogen conduit **125** is maintained at or near atmospheric pressure, and the reforming region is maintained at a pressure of at least 0.5 MPa, or at least 1.0 MPa, or at least 2 MPa, or at least 3 MPa. The reforming region **115** may be maintained at such elevated pressures by injecting the feed and/or steam at high pressures into the reforming region **115**. For example, the feed may comprise high pressure natural gas having a pressure of at least 0.5 MPa, or at least 1.0 MPa, or at least 2.0 MPa, or at least 3.0 MPa that is injected into the reforming region **115**. Alternatively, after exiting the heat exchanger **113** the feed and/or steam may be compressed with compressor **124** to a pressure of at least 0.5 MPa, or at least 1.0 MPa, or at least 2.0 MPa, or at least 3.0 MPa then injected into the reforming reactor **101**.

The temperature at which the feed and steam are mixed and contacted with the reforming catalyst in the reforming region **115** of the reforming reactor **101** is at least 400°C, and preferably may range from 400°C to 650°C, most preferably in a range of from 450°C to 550°C. Unlike typical steam reforming reactions, which produce hydrogen at temperatures in excess of 750°C, the equilibrium of the reforming reaction of the present process is driven towards the production of hydrogen in the reforming reactor **101** operating temperature range of 400°C to 650°C since hydrogen is removed from the reforming region **115** into the hydrogen conduit **125** of the hydrogen separation membrane(s) **103**. An operating temperature of 400°C to 650°C favors the shift reaction as well, converting carbon monoxide and steam to more hydrogen, which is then removed from the reforming region **115** into the hydrogen conduit **125** of the hydrogen separation membrane(s) **103** through the membrane wall member **123** of the membrane(s) **103**. The fuel cell **105** exhausts may be used to provide the required heat to induce the reforming and shift reactions in the reforming region **115** of the reforming reactor **101** through the exhaust conduits **117** and **119**, as described in further detail below.

A non-hydrogen gaseous stream may be removed from the reforming region **115** via line **127**, where the non-hydrogen gaseous stream may include unreacted feed and gaseous non-hydrogen reformed products in the reformed product gas. The non-hydrogen reformed products and unreacted feed may include carbon dioxide, water (as steam), and small amounts of carbon monoxide and unreacted hydrocarbons.

In an embodiment, the non-hydrogen gaseous stream separated from the reforming region **115** may be a carbon dioxide gas stream containing at least 0.9, or at least 0.95, or at least 0.98 mole fraction carbon dioxide on a dry basis. The carbon dioxide gas stream may be a high pressure gas stream, having a pressure of at least 1 MPa, or at least 2 MPa, or at least 2.5 MPa. The high pressure carbon dioxide gas stream may contain significant amounts of water as steam as it exits the reforming reactor **101**. The water may be removed from the high pressure carbon dioxide gas stream by passing the stream through heat exchanger **113** via line **127** to exchange heat with the steam and feed being fed to the reforming reactor **101**, cooling the high pressure carbon dioxide gas stream. The cooled high pressure carbon dioxide gas stream may be cooled further to condense the water from the stream in heat exchanger **129**, where the cooled high pressure carbon dioxide stream may be passed to the heat exchanger **129** from heat exchanger **113** via line **131**. The dry high pressure carbon dioxide stream may be removed from heat exchanger **129** via line **133**. The condensed water may be fed to condenser **151** through line **155**.

The dry high pressure carbon dioxide stream may be expanded through a turbine **135** to drive the turbine **135** and produce a low pressure carbon dioxide stream. Expansion of the dry high pressure carbon dioxide stream through the turbine **135** may be used to generate electricity in addition to electricity generated by the fuel cell **105**. Alternatively, the turbine **135** may be used to drive a compressor **161**, which may be used to compress a gas stream containing hydrogen that is fed to the fuel cell **105** as described below, and/or to drive compressor **124** to compress steam and/or feed being fed to the reforming reactor **101**. The low pressure carbon dioxide stream may be sequestered or used for carbonation of beverages.

Alternatively, the high pressure carbon dioxide stream may not be converted to a low pressure carbon dioxide stream, and may be used for enhancing oil recovery from an oil formation by injecting the high pressure carbon dioxide stream into the oil formation.

A first gas stream containing hydrogen may be separated from the reformed product gas in the reforming reactor **101** by selectively passing hydrogen through the membrane wall member **123** of the hydrogen separation membrane(s) **103** into the hydrogen conduit **125** of the hydrogen separation membrane(s) **103**. The first gas stream may contain a very high concentration of hydrogen, and may contain at least 0.6, or at least 0.7, or at least 0.8, or at least 0.9, or at least 0.95, or at least 0.98 mole fraction hydrogen.

A sweep gas comprising steam may be injected into the hydrogen conduit **125** via line **137** to sweep hydrogen from the inner portion of the membrane wall member **123** into the hydrogen conduit **125**, thereby increasing the rate hydrogen may be separated from the reforming region **115** by the hydrogen separation membrane **103**. The first gas stream and steam sweep gas may be removed from the hydrogen separation membrane **103** and the reforming reactor **101** through hydrogen outlet line **139**.

The first gas stream and the steam sweep gas may be fed to a heat exchanger **141** via hydrogen outlet line **139** to cool the first gas stream and steam sweep gas. The combined first gas stream and steam sweep gas may have a temperature of from 400°C to 650°C, typically a temperature of from 450°C to 550°C, upon exiting the reforming reactor **101**. The combined first gas stream and steam sweep gas may exchange heat with the initial feed and water/steam in the heat exchanger **141**. The initial feed may be provided to the heat exchanger **141** via line **143**, and water/steam may be provided to the heat exchanger **141** via line **145**, where the flow rate of the feed and the water may be regulated by metering valves **142** and **144**, respectively. The heated feed and steam may fed to heat exchanger **113** via lines **147** and **149**, respectively, for further heating prior to being fed to the reforming reactor **101** as described above. The cooled combined first gas stream and steam sweep gas may be fed to condenser **151** through line **152** to condense water from the combined streams by exchanging heat with water fed into the condenser **151** via line **153** and condensed water separated from the high pressure carbon dioxide gas stream via line **155**.

The water condensed in condenser **151** and water fed to the condenser **151** through lines **153** and **155** may be passed through water trap line **157** to a pump **159** which pumps the water to heat exchanger **129** for heat exchange with the cooled high pressure carbon dioxide gas stream to heat the water while further cooling the cooled high pressure carbon dioxide gas stream. The heated water/steam may be passed to the heat exchanger **141** via line **145**, as described above, for further heating to produce steam to be fed to the reforming reactor **101** after further heating in heat exchanger **113**.

The cooled first gas stream containing hydrogen and little or no water may be fed from the condenser **151** to a compressor **161** through line **163**. The first gas stream may have a pressure at or near atmospheric pressure upon exiting the reforming reactor and being fed through heat exchanger **141** and condenser **151** to the compressor **161**. The first gas stream may be compressed in the compressor **161** to increase the pressure of the first gas stream prior to being fed to the fuel cell **105.** In an embodiment, the first gas stream may be compressed to a pressure of from 0.15 MPa to 0.5 MPa, and preferably from 0.2 MPa to 0.3 MPa. Energy to drive the compressor **161** may be provided by expansion of the high pressure carbon dioxide stream through a turbine **135** operatively coupled to drive the compressor **161**.

The first gas stream may then be fed to the anode **107** of the solid oxide fuel cell **105** through line **167** into the anode inlet **165**. The first gas stream provides hydrogen to the anode for electrochemical reaction with an oxidant at one or more anode electrodes along the anode path length in the fuel cell. The rate the first gas stream is fed to the anode **107** of the fuel cell **105** may be selected by selecting the rate that the feed and steam are fed to the reforming reactor **101** which may be controlled by metering valves **142** and **144**.

A second gas stream containing hydrogen may also be fed to the anode **107** of the fuel cell **105**. The second gas stream may be separated from the anode exhaust stream, which contains hydrogen and water. The second gas stream may be separated from the anode exhaust stream by cooling the anode exhaust stream sufficiently to condense water from the anode gas exhaust stream to produce the second gas stream containing hydrogen.

The anode exhaust stream exits the anode **107** through the anode exhaust outlet **169**. The anode exhaust stream may be initially cooled by exchanging heat with steam and feed in the reforming reactor. In an embodiment, the anode exhaust stream may be initially cooled by being fed through line **173** to one or more reformer anode exhaust conduits **119** extending into and located within the reforming region **115** of the reforming reactor **105**. Heat may be exchanged between the anode exhaust stream and the feed and steam in the reforming region **115** of the reforming reactor **101** as the anode exhaust stream passes through the reforming region **115** in the reformer anode exhaust conduit **119**, as described in further detail below, cooling the anode exhaust stream and heating the steam and feed in the reactor **101**.

After exchanging heat with the feed and steam in the reforming region **115** of the reforming reactor **101**, the cooled anode exhaust stream may exit the anode exhaust conduit **119** and may be cooled further to separate the second gas stream containing hydrogen from water in the anode exhaust stream. In one embodiment, to control the flow rate of the second gas stream to the fuel cell **105,** at least a portion of the anode exhaust stream may be passed to heat exchanger **141** via line **174** to further cool the selected portion of the anode exhaust stream by exchange of heat with the feed from line **143** and steam from line **145**, then fed to a condenser **175** to further cool the selected portion of the anode exhaust stream. Hydrogen may be separated from the selected portion of the anode exhaust stream by condensing water from the anode exhaust stream in the condenser **175**. The separated hydrogen may be fed to a hydrogen storage tank **177** through line **179**. Water condensed from condenser **175** may be fed to pump **159** through line **180**.

Cooled anode exhaust stream not fed to condenser **175** for separation into the hydrogen tank is used to provide the second gas stream to the fuel cell **105**. The cooled anode exhaust stream may be passed to heat exchanger **141** via line **174** to further cool the anode exhaust stream by exchange of heat with the feed from line **143** and steam from line **145**, then mixed with the first gas stream and steam sweep gas by feeding the anode exhaust stream through line **181** to line **152**. The mixture of anode exhaust stream, first gas stream, and steam sweep gas may be then fed to condenser **151** to further cool the anode exhaust stream. The second gas stream, derived from condensing water from the anode exhaust stream, may be separated from the condenser **151** via line **163** mixed together with the first gas stream. The second gas stream may contain at least 0.6, or at least 0.7, or at least 0.8, or at least 0.9, or at least 0.95, or at least 0.98 mole fraction hydrogen, where the hydrogen content of the second gas stream may be determined by determining the hydrogen content of the cooled anode exhaust stream on a dry basis. Water from the anode exhaust stream may be condensed in condenser **151** together with water from the first gas stream and the steam sweep gas, and removed from the condenser **151** through line **157** to be fed to pump **159**.

Metering valves **183** and **185** may be used to select the rate of flow of the second gas stream to the solid oxide fuel cell **105**. In order to block the flow of a second gas stream to the fuel cell and to store hydrogen in the hydrogen tank **177**, valve **185** may be completely closed, blocking flow of the anode exhaust stream to the condenser **151** and the second gas stream to the solid oxide fuel cell while valve **183** may be completely opened to allow the anode exhaust stream to flow to condenser **175** and hydrogen to the hydrogen tank **177**. Alternatively, valve **183** may be completely closed, blocking flow of the anode exhaust stream to condenser **175** and hydrogen to the hydrogen tank **177**, and valve **185** may be completely opened to allow the entire anode exhaust stream to flow to the condenser **151** and the second gas stream to flow to the solid oxide fuel cell **105** at a maximum flow rate. The flow rate of the second gas stream to the solid oxide fuel cell may be selected by adjusting valves **183** and **185** in coordination to meter the flow rate of the anode exhaust stream to condenser **151** and the rate of the second gas stream to the solid oxide fuel cell **105**. In a preferred embodiment, the flow rate of the second gas stream to the fuel cell **105** may be automatically controlled to a selected rate by automatically adjusting the metering valves **183** and **185** in response to the water and/or hydrogen content of the anode exhaust stream.

In an embodiment, when the first and second gas streams are combined by adjusting valves **183** and **185** as described above, a small portion of the combined first and second gas streams may be passed through a hydrogen separation device **187** as a bleed stream to remove any small amounts of carbon oxides that may be present in the combined first and second gas streams as a result of imperfect separation of hydrogen from carbon oxides by the hydrogen separation membrane **103** in the reforming reactor **101** when producing the first gas stream and its subsequent recycle in the second gas stream. Valves **189** and **191** may be utilized to control the flow of the bleed stream to the hydrogen separation device **187**, where preferably valves **189** and **191** may permit a metered flow of the combined first and second gas streams simultaneously through lines **193** and **195**, or, alternatively, separately through either line **193** or line **195**. The hydrogen separation device **187** is preferably a pressure swing adsorption apparatus effective for separating hydrogen from carbon oxides, or may be a membrane selectively permeable to hydrogen such as those described above. The first and second gas streams in lines **195** and **197** may be combined to be fed to the solid oxide fuel cell **105** through line **167**.

In an embodiment of the process, the temperature of the first gas stream or the combined first and second gas streams and pressure of the first gas stream or the combined first and second gas streams may be selected for effective operation of the solid oxide fuel cell **105**, and, in particular, the temperature should not be so low as to inhibit the electrochemical reactivity of the fuel cell and should not be so high as to induce an uncontrolled exothermic reaction in the fuel cell **105**. In an embodiment, the temperature of the first gas stream or the combined first and second gas streams may range from 25°C to 300°C, or from 50°C to 200°C, or from 75°C to 150°C. The pressure of the first gas stream or the combined first and second streams may be controlled by the compression provided to the combined first and second gas streams by compressor **161**, and may be from 0.15 MPa to 0.5 MPa, or from 0.2 MPa to 0.3 MPa.

An oxygen containing gas stream may be fed to the cathode **199** of the fuel cell through cathode inlet **201** via line **203**. The oxygen containing gas stream may be provided by an air compressor or an oxygen tank (not shown). In an embodiment, the oxygen containing gas stream may be air or pure oxygen. In another embodiment, the oxygen containing gas stream may be an oxygen enriched air stream containing at least 21%

oxygen, where the oxygen enriched air stream provides higher electrical efficiency in the solid oxide fuel cell than air since the oxygen enriched air stream contains more oxygen for conversion into ionic oxygen in the fuel cell.

The oxygen containing gas stream may be heated prior to being fed to the cathode **199** of the fuel cell **105**. In one embodiment, the oxygen containing gas stream may be heated to a temperature of from 150°C to 350°C prior to being fed to the cathode **199** of the fuel cell **105** in heat exchanger **205** by exchanging heat with a portion of the cathode exhaust provided to the heat exchanger from the cathode exhaust outlet **207** via line **209**. The flow rate of the cathode exhaust stream to the heat exchanger **205** may be controlled with metering valve **211**. Alternatively, the oxygen containing gas stream may be heated by an electrical heater (not shown), or the oxygen containing gas stream may be provided to the cathode **199** of the fuel cell **105** without heating.

The solid oxide fuel cell **105** used in this embodiment of the process of the invention may be a conventional solid oxide fuel cell, preferably having a planar or tubular configuration, and is comprised of an anode **107**, a cathode **199**, and an electrolyte **213** where the electrolyte **213** is interposed between the anode **107** and the cathode **199**. The solid oxide fuel cell may be comprised of a plurality of individual fuel cells stacked together—joined electrically by interconnects and operatively connected so that a fuel may flow through the anodes of the stacked fuel cells and an oxygen containing gas may flow through the cathodes of the stacked fuel cells. As used herein, the term "solid oxide fuel cell" is defined as either a single solid oxide fuel cell or a plurality of operatively connected or stacked solid oxide fuel cells. In an embodiment, the anode **107** is formed of a Ni/ZrO_2 cermet, the cathode **199** is formed of a doped lanthanum manganite or stabilized ZrO_2 impregnated with praseodymium oxide and covered with SnO doped In_2O_3, and the electrolyte **213** is formed of yttria stabilized ZrO_2 (approximately 8 mol% Y_2O_3). The interconnect between stacked individual fuel cells or tubular fuel cells may be a doped lanthanum chromite.

The solid oxide fuel cell **105** is configured so that the first gas stream or the combined first and second gas streams may flow through the anode **107** of the fuel cell **105** from the anode inlet **165** to the anode exhaust outlet **169**, contacting one or more anode electrodes over the anode path length from the anode inlet **165** to the anode exhaust outlet **169**. The fuel cell **105** is also configured so that the oxygen containing gas may flow through the cathode **199** from the cathode inlet **201** to the cathode exhaust outlet **207**, contacting one or more cathode electrodes over the cathode path length from the cathode inlet **201** to the cathode exhaust outlet **207**. The electrolyte **213** is positioned in the fuel cell **105** to prevent the first gas stream or combined first and second gas stream from entering the cathode and to prevent the oxygen containing gas from entering the anode, and to conduct ionic oxygen from the cathode to the anode for electrochemical reaction with hydrogen in the first gas stream or the combined first and second gas streams at the one or more anode electrodes.

The solid oxide fuel cell **105** is operated at a temperature effective to enable ionic oxygen to traverse the electrolyte **213** from the cathode **199** to the anode **107** of the fuel cell **105**. The solid oxide fuel cell **105** may be operated at a temperature of from 700°C to 1100°C, or from 800°C to 1000°C. The oxidation of hydrogen with ionic oxygen at the one or more anode electrodes is a very exothermic reaction, and the heat of reaction generates the heat required to operate the solid oxide fuel cell **105**. The temperature at which the solid oxide fuel cell is operated may be controlled by independently controlling the temperature of the first gas stream, the temperature of the second gas stream fed to the fuel cell (if any), and the oxygen containing gas stream, and the flow rates that these streams are fed to the fuel cell **105**. In an embodiment, the temperature of the second gas stream fed to the fuel cell is controlled to a temperature of at most 100°C, the temperature of the oxygen containing gas stream is controlled to a temperature of at most 300°C, and the temperature of the first gas stream is controlled to a temperature of at most 550°C to maintain the operating temperature of the solid oxide fuel cell in a range from 700°C to 1000°C, and preferably in a range of from 800°C to 900°C.

To initiate operation of the fuel cell **105**, the fuel cell **105** is heated to its operating temperature. In a preferred embodiment, operation of the solid oxide fuel cell **105** may be initiated by generating a hydrogen containing gas stream in a catalytic partial oxidation reforming reactor **221** and feeding the hydrogen containing gas stream through line **223** to the anode **107** of the solid oxide fuel cell. A hydrogen containing gas stream may be generated in the catalytic partial oxidation reforming reactor by combusting a hydrocarbon feed and an oxygen source in the catalytic partial oxidation reforming reactor **221** in the presence of a conventional partial oxidation reforming catalyst, where the oxygen source is fed to the catalytic partial oxidation reforming reactor in a substoichiometric amount relative to the hydrocarbon feed.

The hydrocarbon feed fed to the catalytic partial oxidation reforming reactor **221** may be a liquid or gaseous hydrocarbon or mixtures of hydrocarbons, and preferably is methane, natural gas, or other low molecular weight hydrocarbon or mixture of low molecular weight hydrocarbons. In a particularly preferred embodiment of the process of the invention, the hydrocarbon feed fed to the catalytic partial oxidation reforming reactor **221** may be a feed of the same type as used in the reforming reactor **101** to reduce the number of hydrocarbon feeds required run the process.

The oxygen containing feed fed to the catalytic partial oxidation reforming reactor **221** may be pure oxygen, air, or oxygen enriched air. The oxygen containing feed should be fed to the catalytic partial oxidation reforming reactor **221** in substoichiometric amounts relative to the hydrocarbon feed to combust with the hydrocarbon feed in the catalytic partial oxidation reforming reactor **221**.

The hydrogen containing gas stream formed by combustion of the hydrocarbon feed and the oxygen containing gas in the catalytic partial oxidation reforming reactor **221** contains compounds that may be oxidized in the anode **107** of the fuel cell **105** by contact with an oxidant at one or more of the anode electrodes, including hydrogen and carbon monoxide, as well as other compounds such as carbon dioxide. The hydrogen containing gas steam from the catalyst partial oxidation reforming reactor **221** preferably does not contain compounds that may oxidize the one or more anode electrodes in the anode **107** of the fuel cell **105**.

The hydrogen containing gas stream formed in the catalytic partial oxidation reforming reactor **221** is hot, and may have a temperature of at least 700°C, or from 700°C to 1100°C, or from 800°C to 1000°C. Use of the hot hydrogen containing gas stream from the catalytic partial oxidation reforming reactor **221** to initiate start up of the solid oxide fuel cell **105** is preferred in the process of the invention since it enables the temperature of the fuel cell **105** to be raised to the operating temperature of the fuel cell **105** almost instantaneously. In an embodiment, heat may be exchanged in heat exchanger **205** between the hot hydrogen containing gas from the catalytic partial oxidation reforming reactor and an oxygen containing gas fed to the cathode **199** of the fuel cell **105** when initiating operation of the fuel cell **105** to heat the oxygen containing gas.

Upon reaching the operating temperature of the fuel cell **105**, the flow of the hot hydrogen containing gas stream from the catalytic partial oxidation reforming reactor **221** into the fuel cell **105** may be shut off by valve **225**, while feeding the first gas stream from the reforming reactor **101**into the anode **107** by opening valve **227**. Continuous operation of the fuel cell may then conducted according to the process of the invention.

In another embodiment (not shown in Fig. 1), operation of the fuel cell may be initiated with a hydrogen start-up gas stream from the hydrogen storage tank **177**, where the hydrogen start-up gas stream is passed through a start-up heater to bring the fuel cell up to its operating temperature prior to introducing the first gas stream into the fuel cell. The hydrogen storage tank **177** may be operatively connected to the fuel cell to permit introduction of the hydrogen start-up gas stream into the anode of the solid oxide fuel cell. The start-up heater may indirectly heat the hydrogen start-up gas stream to a temperature of from 750°C to 1000°C. The start-up heater may be an electrical heater or may be a combustion heater. Upon reaching the operating temperature of the fuel cell, the flow of the hydrogen start-up gas stream into the fuel cell may be shut off by a valve, and the first gas stream and the oxygen containing gas stream may be introduced into the fuel cell to start the operation of the fuel cell.

Referring again to Fig. 1, during initiation of operation of the fuel cell **105,** a oxygen containing gas stream may be introduced into the cathode **199** of the fuel cell **105**. The oxygen containing gas stream may be air, oxygen enriched air containing at least 21% oxygen, or pure oxygen. Preferably, the oxygen containing gas stream is the oxygen containing gas stream that will be fed to the cathode **199** during operation of the fuel cell **105** after initiating operation of the fuel cell.

In a preferred embodiment, the oxygen containing gas stream fed to the cathode **199** of the fuel cell during start-up of the fuel cell has a temperature of at least 500°C, more preferably at least 650°C, and more preferably at least 750°C. The oxygen containing gas stream may be heated by an electric heater before being fed to the cathode **199** of the solid oxide fuel cell **105**. In a preferred embodiment, the oxygen containing gas stream used in initiating operation of the fuel cell **105** may be heated by heat exchange with the hot hydrogen containing gas stream from a catalytic partial oxidation reforming reaction in heat exchanger **205** prior to being fed to the cathode **199** of the fuel cell **105**.

Once operation of the fuel cell **105** has commenced, the first gas stream or the combined first and second gas streams may be mixed with an ionic oxygen oxidant at one or more anode electrodes in the fuel cell **105** to generate electricity. The ionic oxygen oxidant is derived from oxygen in the oxygen-containing gas stream flowing through the cathode **199** of the fuel cell **105** and conducted across the electrolyte **213** of the fuel cell.

The first gas stream or the combined first and second gas streams fed to the anode **107** of the fuel cell **105** and the oxidant are mixed in the anode **107** at the one or more anode electrodes of the fuel cell **105** by feeding the first gas stream, the second gas stream (if any), and the oxygen containing gas stream to the fuel cell **105** at selected independent rates while operating the fuel cell at a temperature of from 750°C to 1100°C.

The first gas stream or the combined first and second gas streams and the oxidant are preferably mixed at the one or more anode electrodes of the fuel cell **105** to generate electricity at an electrical power density of at least 0.4 W/cm^2, more preferably at least 0.5 W/cm^2, or at least 0.75 W/cm^2, or at least 1 W/cm^2, or at least 1.25 W/cm^2, or at least 1.5 W/cm^2. Electricity may be generated at such electrical power densities by selecting and controlling the rate that the first gas stream is fed to the anode **107** of the fuel cell **105** or independently selecting and controlling the flow rates of the first gas stream and the second gas stream to the anode **109** of the fuel cell **105**. The flow rate of the first gas stream to the anode **107** of the fuel cell **105** may be selected and controlled by selecting and controlling the rate that the feed and steam are fed to the reforming reactor by adjusting metering valves **142** and **144**. The flow rate of the second gas stream to the anode **107** of the fuel cell **105** may be selected and controlled by selecting and controlling the flow rate of the anode exhaust stream to the condenser **151** by adjusting metering valves **183** and **185** as described above. In an embodiment, metering valves **183** and **185** may be automatically adjusted by a feedback circuit (not shown) that measures water and/or hydrogen content in the anode exhaust stream to select the rate the second gas stream is fed to the fuel cell **105**, and adjusts the metering valves **183** and **185** to maintain a selected water and/or hydrogen content in the anode exhaust stream by adjusting the rate that the second gas stream is fed to the fuel cell **105**.

In the process of the invention, mixing the first gas stream or the combined first and second gas streams and the oxidant at the one or more anode electrodes generates water (as steam) by the oxidation of a portion of hydrogen present in the first gas stream or the combined first and second gas streams fed to the fuel cell **105** with the oxidant. Water generated by the oxidation of hydrogen with an oxidant is swept through the anode **107** of the fuel cell **105** by the unreacted portion of the first gas stream or the combined first and second gas streams to exit the anode **107** as part of the anode exhaust stream.

In an embodiment of the process of the invention, the flow rate that the first gas stream is fed to the anode **107** and, if a second gas stream is provided to the anode **107**, the flow rate that the second gas stream is fed to the anode **107** may be independently selected so the ratio of amount of water formed in the fuel cell per unit of time to the amount of hydrogen in the anode exhaust per unit of time is at most 1.0, or at most 0.75, or at most 0.67, or at most 0.43, or at most 0.25, or at most 0.11. In an embodiment, the amount of water formed in the fuel cell and the amount of hydrogen in the anode exhaust may be measured in moles so that the ratio of the amount of water formed in the fuel cell per unit of time to the amount of hydrogen in the anode exhaust per unit of time in moles per unit of time is at most 1.0, or at most 0.75, or at most 0.67, or at most 0.43, or at most 0.25, or at most 0.11. In another embodiment of the process of the invention, the flow rate that the first gas stream is fed to the anode **107** and, if a second gas stream is provided to the anode **107**, the flow rate that the second gas stream is fed to the anode **107** may be independently selected so the anode exhaust stream contains at least 0.6, or at least 0.7, or at least 0.8, or at least 0.9 mole fraction hydrogen. In an embodiment, the flow rate that the first gas stream is fed to the anode **107** and, if a second gas stream is provided to the anode, the flow rate that the second gas stream is fed to the anode **107** may be independently selected so the anode exhaust stream contains at least 50%, or at least 60%, or at least 70%, or at least 80%, or at least 90% of the hydrogen in the combined first and second gas streams fed to the anode **107,** or, if only the first gas stream is provided to the anode **107**, the anode exhaust stream contains at least 50%, or at least 60%, or at least 70%, or at least 80%, or at least 90% of the hydrogen in the first gas stream provided to the anode **107**. In an embodiment, the flow rate that the first gas stream is fed to the anode **107**, and, if a second gas stream is provided to the anode **107**, the flow rate that the second gas stream is provided to the anode **107** may be independently selected so the per pass hydrogen utilization in the fuel cell is at most 50%, or at most 40%, or at most 30%, or at most 20%, or at most 10%.

The flow rate of the oxygen containing gas stream provided to the cathode **199** of the solid oxide fuel cell **105** should be selected to provide sufficient oxidant to the anode to generate electricity at an electrical power density of at least 0.4 W/cm^2, or at least 0.5 W/cm^2, or at least 0.75 W/cm^2, or at least 1 W/cm^2, or at least 1.25 W/cm^2, or at least 1.5 W/cm^2 when combined with the fuel from the first gas stream or the combined first and second gas streams at the one or more anode electrodes. The flow rate of the oxygen containing gas stream to the cathode **199** may be selected and controlled by adjusting metering valve **215**.

The reforming reactor **101** and the solid oxide fuel cell **105** may be thermally integrated so the heat from the exothermic electrochemical reaction in the fuel cell **105** is provided to the reforming region **115** of the reforming reactor **101** to drive the endothermic reforming reaction in the reforming reactor **101**. As described above, one or more anode exhaust conduits **119** and/or one or more cathode exhaust conduits **117** extend into and are located within the reforming region **115** of the reforming reactor **101**. A hot anode exhaust stream may exit the anode **107** of the fuel cell **105** from the anode exhaust outlet **169** and enter the anode exhaust conduit **119** in the reforming region **115** via line **173**, and/or a hot cathode exhaust stream may exit the cathode **199** of the fuel cell **105** from the cathode exhaust outlet **207** and enter the cathode exhaust conduit **117** in the reforming region **115** via line **217**. Heat from the hot anode exhaust stream may be exchanged between the anode exhaust stream and the mixture of steam and feed in the reforming region **115** as the anode exhaust stream passes through the anode exhaust conduit **119**. Likewise, heat from the hot cathode exhaust stream may be exchanged between the cathode exhaust stream and the mixture of steam and feed in the reforming region **115** of the reforming reactor **101** as the cathode exhaust stream passes through the cathode exhaust conduit **117**.

The heat exchange from the exothermic solid oxide fuel cell **105** to the endothermic reforming reactor **101** is highly efficient. Location of the anode exhaust conduit(s) **119** and/or the cathode exhaust conduit(s) **117** within the reforming region **115** of the reforming reactor **101** permits exchange of heat between the hot anode and/or cathode exhaust streams and the mixture of feed and steam within the reactor **101**, transferring heat to the feed and steam at the location that the reforming reaction takes place. Further, location of the anode and/or cathode exhaust conduits **119** and **117** within the reforming region **115** permits the hot anode and/or cathode exhaust streams to heat the reforming catalyst in the reforming region **115** as a result of the close proximity of the conduits **117** and **119** to the catalyst bed.

Further, no additional heat other than provided by either 1) the anode exhaust stream; or 2) the cathode exhaust stream; or 3) the anode exhaust stream in combination with the cathode exhaust stream, needs to be provided to the reforming reactor **101** to drive the reforming and shift reactions in the reactor **101** to produce the reformed product gas and the first gas stream. As noted above, the temperature required to run the reforming and shift reactions within the reforming reactor **101** is from 400°C to 650°C, which is much lower than conventional reforming reactor temperatures—which are at least 750°C, and typically 800°C-900°C. The reforming reactor may be run at such low temperatures due to the equilibrium shift in the reforming reaction engendered by separation of hydrogen from the reforming reactor **101** by the high temperature hydrogen separation membrane **103**. The anode exhaust stream and the cathode exhaust stream may have a temperature of from 800°C to 1000°C, which, upon heat exchange between the anode exhaust stream and/or the cathode exhaust stream and the mixture of feed and steam, is sufficient to drive the lower temperature reforming and shift reactions in the reforming reactor **101**.

In an embodiment of the process of the invention, the exchange of heat between the anode exhaust stream and the mixture of steam and feed in the reforming region **115** as the anode exhaust stream passes through the anode exhaust conduit **119** may provide a significant amount of the heat provided to the mixture of steam and feed in the reactor **101** to drive the reforming and shift reactions. In an embodiment of the process of the invention, the exchange of heat between the anode exhaust stream and the mixture of steam and feed in the reactor **101** may provide at least 40%, or at least 50%, or at least 70%, or at least 90% of the heat provided to the mixture of steam and feed in the reactor **101**. In an embodiment, the heat supplied to the mixture of steam and feed in the reforming reactor **101** consists essentially of the heat exchanged between the anode exhaust stream passing through the anode exhaust conduit **119** and the mixture of steam and feed in the reforming reactor **101**. In an embodiment of the process, the exchange of heat between the anode exhaust stream and the mixture of steam and feed in the reactor **101** may be controlled to maintain the temperature of the mixture of steam and feed in a range of from 400°C to 650°C.

In an embodiment of the process of the invention, the exchange of heat between the cathode exhaust stream and the mixture of steam and feed in the reforming region **115** as the cathode exhaust stream passes through the cathode exhaust conduit **119** may provide a significant amount of the heat provided to the mixture of steam and feed in the reactor **101** to drive the reforming and shift reactions. In an embodiment of the process of the invention, the exchange of heat between the cathode exhaust stream and the mixture of steam and feed in the reactor **101** may provide at least 40%, or at least 50%, or at least 70%, or at least 90% of the heat provided to the mixture of steam and feed in the reactor **101**. In an embodiment, the heat supplied to the mixture of steam and feed in the reforming reactor **101** consists essentially of the heat exchanged between the cathode exhaust stream passing through the cathode exhaust conduit **119** and the mixture of steam and feed in the reforming reactor **101**. In an embodiment of the process, the exchange of heat between the cathode exhaust stream and the mixture of steam and feed in the reactor **101** may be controlled to maintain the temperature of the mixture of steam and feed in a range of from 400°C to 650°C.

In an embodiment, the exchange of heat between the anode exhaust stream, the cathode exhaust stream, and the mixture of steam and feed in the reforming region **115** as the anode exhaust stream passes through the anode exhaust conduit **119** and the cathode exhaust stream passes through the cathode exhaust conduit **117** may provide a significant amount of the heat provided to the mixture of steam and feed in the reactor **101** to drive the reforming and shift reactions. In an embodiment of the process of the invention, the exchange of heat between the cathode exhaust stream and the mixture of steam and feed in the reactor **101** may provide up to 60%, or up to 50%, or up to 40%, or up to 30%, or up to 20% of the heat provided to the mixture of steam and feed in the reactor **101** while the exchange of heat between the anode exhaust stream and the mixture of steam and feed may provide at least 40%, or at least 50%, or at least 60%, or at least 70%, or at least 80% of the heat provided to the mixture of steam and feed in the reactor **101**. In an embodiment, the heat supplied to the mixture of steam and feed in the reforming reactor **101** may consist essentially of heat exchanged between the anode and cathode exhaust streams and the mixture of steam and feed in the reactor **101**. In an embodiment of the process, the exchange of heat between the anode and cathode exhaust streams and the mixture of steam and feed in the reactor **101** may be controlled to maintain the temperature of the mixture of steam and feed in a range of from 400°C to 650°C.

In a preferred embodiment, the heat provided by the anode exhaust stream or the anode and cathode exhaust streams to the mixture of steam and feed in the reforming reactor **101** is sufficient to drive the reforming and shift reactions in the reforming reactor **101** such that no other source of heat is required to drive the reactions in the reforming reactor **101**. Most preferably, no heat is provided to the mixture of steam and feed in the reactor **101** by combustion.

In an embodiment, the anode exhaust stream provides most, or all, of the heat to the mixture of steam and feed in the reforming reactor **101** to drive the reforming and shift reactions in the reactor. In this embodiment only some, or none, of the cathode exhaust stream is required to exchange heat with the mixture of steam and feed in the reforming reactor **101** to drive the reforming and shift reactions. The flow of the cathode exhaust stream through the cathode exhaust conduit **117** in the reforming reactor may be controlled to control the amount of heat provided to the mixture of steam and feed in the reforming reactor **101** from the cathode exhaust stream. Metering valves **211** and **220** may be adjusted to control the flow of the cathode exhaust stream to the cathode exhaust conduit **117** such that the cathode exhaust stream provides the desired amount of heat, if any, to the mixture of steam and feed in the reactor **101**. Cathode exhaust stream that is not required to heat the mixture of steam and feed in the reactor **101** may be shunted through line **209** to heat exchanger **205** to heat the oxygen containing gas fed to the cathode.

In an embodiment, the cathode exhaust stream provides most, or all, of the heat to the mixture of steam and feed in the reforming reactor **101** to drive the reforming and shift reactions in the reactor. In this embodiment only some, or none, of the anode exhaust stream is required to exchange heat with the mixture of steam and feed in the reforming reactor **101** to drive the reforming and shift reactions. The flow of the anode exhaust stream through the anode exhaust conduit **119** in the reforming reactor may be controlled to control the amount of heat provided to the mixture of steam and feed in the reforming reactor **101** from the anode exhaust stream. The portion of the anode exhaust stream not used to provide heat to the reforming reactor **101** may be fed through heat exchanger **113** to heat the feed and steam entering the reforming reactor **101** and cool the anode exhaust stream prior to being combined with the first gas stream and steam sweep gas for further cooling in heat exchanger **141**.

The cooled cathode exhaust stream that has passed through the cathode exhaust conduit **117** may still have a significant amount of heat therein, and may have a temperature of up to 650°C. The cooled cathode exhaust stream may be passed out of the cathode exhaust conduit through outlet **218** to be fed to the oxygen containing gas heat exchanger **205** through line **219** along with any cathode exhaust stream metered to the heat exchanger **205** through valve **211**.

In this embodiment of the process of the present invention, relatively little carbon dioxide is generated per unit of electricity produced by the process. The thermal integration of the reforming reactor **101** with the fuel cell **105**—wherein the heat produced in the fuel cell **105** is transferred within the reforming reactor **101** by the anode and/or cathode exhausts from the fuel cell **105**—reduces the energy required to be provided to drive the endothermic reforming reaction, reducing the need to provide such energy, for example by combustion, thereby reducing the amount of carbon dioxide produced in providing energy to drive the reforming reaction. Additionally, where the second gas stream is separated from the anode exhaust stream and recycled back to the fuel cell **105** as fuel, the hydrogen from the anode exhaust stream in the second gas stream to the fuel cell **105** reduces the amount of hydrogen required to be produced by the reforming reactor **101**, thereby reducing attendant carbon dioxide by-product production.

In this embodiment of the process of the present invention, carbon dioxide is generated at a rate of no more than 400 grams per kilowatt-hour (400g per kWh) of electricity generated. In a preferred embodiment, carbon dioxide is generated in the process of the present invention at a rate of no more than 350g per kWh, and in a more preferred embodiment, carbon dioxide is generated in the process of the present invention at a rate of no more than 300g per kWh.

In another embodiment, as shown in Fig. 2, the process of the present invention may use a liquid hydrocarbon feed precursor that may be hydrocracked, and in an embodiment partially reformed, to a gaseous hydrocarbon feed in a pre-reforming reactor **314** which may then be reformed in a hydrogen-separating steam reforming reactor **301** to produce hydrogen which may be utilized to generate electricity in a solid oxide fuel cell **305**. The process is thermally integrated, where heat to drive the endothermic pre-reforming reactor **314** and reforming reactor **301** may be provided from the exothermic solid oxide fuel cell **305** directly within the pre-reforming reactor **314** and/or the reforming reactor **301**.

A steam reforming reactor **301** including one or more high temperature hydrogen-separating membranes **303** is operatively coupled to a solid oxide fuel cell **305** to provide a first gas stream containing primarily hydrogen to the anode **307** of the fuel cell **305** so that electricity may be generated in the fuel cell **305**. A pre-reforming reactor **314** is operatively coupled to the steam reforming reactor **301** to provide a gaseous hydrocarbon feed to the reforming reactor **301** from a liquid hydrocarbon feed. The fuel cell **305** is operatively coupled to the reforming reactor **301** and the pre-reforming reactor **314** so the fuel cell **305** may provide the heat to the reforming reactor **301** necessary to drive the reforming and shift reactions in the reactor **301** and may provide the heat to the pre-reforming reactor **314** necessary to convert a liquid hydrocarbon feed precursor into a gaseous hydrocarbon feed that may be reformed in the reforming reactor **301**.

In this process, a feed precursor comprising a hydrogen source that contains a liquid hydrocarbon may be fed to the pre-reforming reactor **314** via line **308**. The feed precursor may contain one or more of any vaporizable hydrocarbon that is liquid at 20°C at atmospheric pressure (optionally oxygenated) that is vaporizable at temperatures up to 400°C at atmospheric pressure. Such feed precursors may include, but are not limited to, light petroleum fractions such as naphtha, diesel, and kerosene having boiling point range of 50-205°C. The feed precursor may optionally contain some hydrocarbons that are gaseous at 25°C such as methane, ethane, propane, or other compounds containing from one to four carbon atoms that are gaseous at 25°C. In a preferred embodiment, the feed precursor may be diesel fuel. Steam may be fed to the pre-reformer **314** via line **312** to be mixed with the feed precursor in a pre-reforming region **316** of the pre-reformer **314**.

The feed precursor and the steam may be fed to the pre-reformer **314** at a temperature of from 250°C to 650°C, where the feed precursor and steam may be heated to the desired temperature in heat exchanger **313** as described below. The feed precursor may be hydrocracked and vaporized to form the gaseous hydrocarbon feed in the pre-reforming reactor **314** as described more fully below. In an embodiment, the feed precursor may be partially reformed as it is hydrocracked and vaporized to form the feed. Feed and steam from the pre-reforming reactor **314** may be fed to the reforming reactor **301** at a temperature of from 300°C to 650°C.

The feed precursor may be desulfurized in a desulfurizer **321** prior to being heated in the heat exchanger **313**, or optionally after being heated in the heat exchanger **313**, but before being fed to the pre-reforming reactor **314**, to remove sulfur from the feed precursor so the feed precursor does not poison any catalyst in the pre-reforming reactor **314**. The feed precursor may be desulfurized in the desulfurizer **321** by contact with a conventional hydrodesulfurizing catalyst under conventional desulfurizing conditions.

The feed precursor and steam are fed into a pre-reforming region **316** in the pre-reforming reactor **314**. The pre-reforming region **316** may, and preferably does, contain a pre-reforming catalyst therein. The pre-reforming catalyst may be a conventional pre-reforming catalyst, and may be any known in the art. Typical pre-reforming catalysts which can be used include, but are not limited to, Group VIII transition metals, particularly nickel and a support or substrate that is inert under high temperature reaction conditions. Suitable inert compounds for use as a support for the high temperature pre-reforming/hydrocracking catalyst include, but are not limited to, α-alumina and zirconia.

The feed precursor and steam are mixed and contacted with the pre-reforming catalyst in the pre-reforming region **316** of the pre-reforming reactor **314** at a temperature effective to vaporize the feed precursor to form the feed. Mixing and contacting the feed precursor and steam in the pre-reforming reactor **314** with a pre-reforming catalyst at a temperature effective to vaporize the feed precursor may crack hydrocarbons in the feed precursor to reduce the carbon chain length of the hydrocarbons so that the cracked hydrocarbons may be easily steam reformed in the reforming reactor **301**. In an embodiment, the feed precursor and steam are mixed and contacted with the pre-reforming catalyst at a temperature of at least 600°C, or from 700°C to 1000°C, or from 700°C to 900°C; and at a pressure of from 0.1 MPa to 3 MPa, preferably from 0.1 MPa to 1 MPa, or from 0.2 MPa to 0.5 MPa **(correct temperature ranges?)**. As discussed below, heat is supplied to drive the endothermic pre-reforming reaction from the anode exhaust stream and/or from the cathode exhaust stream of the fuel cell **305** through one or more pre-reformer anode exhaust conduits **320** and/or one or more pre-reformer cathode exhaust conduits **322**, respectively, extending into the pre-reforming region **316** of the pre-reforming reactor **314**.

In an embodiment, an excess of steam may be fed to the pre-reforming reactor **314** relative to the amount of hydrocarbons fed to the pre-reforming reactor **314** in the feed precursor. The excess steam may prevent the pre-reforming catalyst from being coked during the pre-reforming reaction. The excess steam may also be fed to the steam reforming reactor **301** from the pre-reforming reactor **314** along with the feed produced in the pre-reforming reactor, where the steam fed to the reforming reactor **301** may be used in the reforming reactor **301** in the reforming reactions and shift reactions in the reforming reactor **301**. The ratio of amount of steam fed to the pre-reforming reactor relative to the amount of feed precursor, in volume or in moles, may be at least 2:1 or at least 3:1, or at least 4:1, or at least 5:1.

The feed precursor vaporized, optionally cracked, and optionally partially reformed in the pre-reforming reactor **314** forms the feed that may be fed to the reforming reactor **301**. The temperature and pressure conditions in the pre-reforming region **316** of the pre-reforming reactor **314** may be selected so the feed formed in the pre-reforming reactor **314** contains primarily light hydrocarbons that are gaseous at 25°C, typically containing from one to four carbons in each molecule. The feed formed in the pre-reforming reactor may include, but is not limited to, methane, methanol, ethane, ethanol, propane, and butane. Preferably, the temperature and pressure of the pre-reforming reactor are controlled to produce a feed containing at least 50 vol.%, or at least 60 vol.%, or at least 80 vol.%

methane. In an embodiment, when the pre-reforming reactor **314** at least partially reforms the feed precursor, the feed fed from the pre-reforming reactor **314** to the reforming reactor **301** may contain hydrogen and carbon monoxide.

Upon formation of the feed in the pre-reforming reactor **314**, the feed and the remaining steam may be fed from the pre-reforming reactor **314** to the reforming reactor **301** via line **309** at a temperature of from 350°C to 650°C, where the feed and steam carry the heat from the pre-reforming reactor **314** into the reforming reactor **301**. The mixture of feed and steam from the pre-reforming reactor **314** may be compressed with compressor **324** prior to being fed to the reforming reactor **301** so the pressure within the reforming reactor **301** is such that hydrogen produced in the reforming reactor **301** may be separated from the reforming reactor **301** through a high temperature hydrogen-separation membrane **303** located in the reforming reactor **301**. The mixture of feed and steam may be compressed to a pressure of at least 0.5 MPa, or at least 1 MPa, or at least 2 MPa, or at least 3 MPa.

If necessary, additional steam may be fed into the reforming region **315** of the reforming reactor **301** from steam heated in heat exchanger **313**. The additional steam may be fed from heat exchanger **313** to the reforming reactor **301** through line **311**. Metering valve **310** may be used to regulate the amount of steam fed from heat exchanger **313** to the reforming reactor **301**. Compressor **330** may be used to compress the steam to the pressure that the mixture of feed and steam are being fed to the reforming reactor **301**.

The mixture of feed and steam from the pre-reforming reactor **314**, and optionally additional steam from heat exchanger **313**, may be fed into a reforming region **315** in the reforming reactor **301**. The reforming region **315** may, and preferably does, contain a reforming catalyst therein. The reforming catalyst may be a conventional steam reforming catalyst, and may be any known in the art. Typical steam reforming catalysts which can be used include, but are not limited to, Group VIII transition metals, particularly nickel. It is often desirable to support the reforming catalysts on a refractory substrate (or support). The support, if used, is preferably an inert compound. Suitable inert compounds for use as a support contain elements of Group III and IV of the Periodic Table, such as, for example the oxides or carbides of Al, Si, Ti, Mg, Ce and Zr.

The feed and steam are mixed and contacted with the reforming catalyst in the reforming region **315** at a temperature effective to form a reformed product gas containing hydrogen and carbon oxides. The reformed product gas may be formed by steam reforming the hydrocarbons in the feed. The reformed product gas may also be formed by shift reacting carbon monoxide in the feed and/or produced by steam reforming with additional steam. The reformed product gas may contain hydrogen and at least one carbon oxide. Carbon oxides that may be in the reformed product gas include carbon monoxide and carbon dioxide.

One or more high temperature tubular hydrogen-separation membranes **303** may be located in the reforming region **315** of the reforming reactor **301** positioned so the reformed product gas may contact the hydrogen-separation membrane(s) **303** and hydrogen may pass through the membrane wall member **323** to a hydrogen conduit **325** located within the tubular membrane **303**. The membrane wall member **323** separates the hydrogen conduit **325** from gaseous communication with non-hydrogen compounds of reformed product gas, feed, and steam in the reforming region **315**, and is selectively permeable to hydrogen, elemental and/or molecular, so that hydrogen in the reformed product gas may pass through the membrane wall member **323** to the hydrogen conduit **325** while other gases in the reforming region are prevented by the membrane wall member **323** from passing to the hydrogen conduit **325**.

The high temperature tubular hydrogen-separation membrane(s) **303** in the reforming region may comprise a support coated with a thin layer of a metal or alloy that is selectively permeable to hydrogen. The support may be formed of a ceramic or metallic material that is porous to hydrogen. Porous stainless steel or porous alumina are preferred materials for the support of the membrane **303.** The hydrogen selective metal or alloy coated on the support may be selected from metals of Group VIII, including, but not limited to Pd, Pt, Ni, Ag, Ta, V, Y, Nb, Ce, In, Ho, La, Au, and Ru, particularly in the form of alloys. Palladium and platinum alloys are preferred. A particularly preferred membrane **303** used in the present process has a very thin film of a palladium alloy having a high surface area coating a porous stainless steel support. Membranes of this type can be prepared using the methods disclosed in U.S. Pat. No. 6,152,987. Thin films of platinum or platinum alloys having a high surface area would also be suitable as the hydrogen selective material.

The pressure within the reforming region **315** of the reforming reactor **301** is maintained at a level significantly above the pressure within the hydrogen conduit **325** of the tubular membrane **303** so that hydrogen is forced through the membrane wall member **323** from the reforming region **315** of the reforming reactor into the hydrogen conduit **125**.

In an embodiment, the hydrogen conduit **325** is maintained at or near atmospheric pressure, and the reforming region is maintained at a pressure of at least 0.5 MPa, or at least 1.0 MPa, or at least 2 MPa, or at least 3 MPa. As noted above, the reforming region **315** may be maintained at such elevated pressures by compressing the mixture of steam and feed from the pre-reforming reactor with compressor **324** and injecting the mixture of feed and steam at high pressures into the reforming region **315**. Alternatively, the reforming region **315** may be maintained at such high pressures by compressing additional steam from heat exchanger **313** with compressor **330** and injecting the high pressure steam into the reforming region **315** of the reforming reactor **301**. The reforming region **315** of the reforming reactor **301** may be maintained at a pressure of at least 0.5 MPa, or at least 1.0 MPa, or at least 2.0 MPa, or at least 3.0 MPa.

The temperature at which the feed and steam are mixed and contacted with the reforming catalyst in the reforming region **315** of the reforming reactor **301** is at least 400°C, and preferably may range from 400°C to 650°C, most preferably in a range of from 450°C to 550°C. As noted above, unlike typical steam reforming reactions, which produce hydrogen at temperatures in excess of 750°C, the equilibrium of the reforming reaction of the present process is driven towards the production of hydrogen in the reforming reactor **301** operating temperature range of 400°C to 650°C since hydrogen is removed from the reforming region **315** into the hydrogen conduit **325** of the hydrogen separation membrane(s) **303**. An operating temperature of 400°C to 650°C favors the shift reaction as well, converting carbon monoxide and steam to more hydrogen, which is then removed from the reforming region **315** into the hydrogen conduit **325** of the hydrogen separation membrane(s) **303** through the membrane wall member **323** of the membrane(s) **303**. The fuel cell **305** exhausts may be used to provide the required heat to induce the reforming and shift reactions in the reforming region **315** of the reforming reactor **301** through the exhaust conduits **317** and **319**, as described in further detail below.

A non-hydrogen gaseous stream may be removed from the reforming region **315** via line **327**, where the non-hydrogen gaseous stream may include unreacted feed and gaseous non-hydrogen reformed products in the reformed product gas. The non-hydrogen reformed products and unreacted feed may include carbon dioxide, water (as steam), and small amounts of carbon monoxide and unreacted hydrocarbons.

In an embodiment, the non-hydrogen gaseous stream separated from the reforming region **315** may be a carbon dioxide gas stream containing at least 0.9, or at least 0.95, or at least 0.98 mole fraction carbon dioxide on a dry basis. The carbon dioxide gas stream may be a high pressure gas stream, having a pressure of at least 1 MPa, or at least 2 MPa, or at least 2.5 MPa. The high pressure carbon dioxide gas stream may contain significant amounts of water as steam as it exits the reforming reactor **301**. The water may be removed from the high pressure carbon dioxide gas stream by passing the stream through heat exchanger **313** via line **327** to exchange heat with the steam and feed precursor being fed to the pre-reforming reactor **314**, cooling the high pressure carbon dioxide gas stream. The cooled high pressure carbon dioxide gas stream may be cooled further to condense the water from the stream in heat exchanger **329**, where the cooled high pressure carbon dioxide stream may be passed to the heat exchanger **329** from heat exchanger **313** via line **331**. The dry high pressure carbon dioxide stream may be removed from heat exchanger **329** via line **333**. The condensed water may be fed to condenser **351** through line **355**.

The dry high pressure carbon dioxide stream may be expanded through a turbine **335** to drive the turbine **335** and produce a low pressure carbon dioxide stream. The turbine **335** may be used to generate electricity in addition to electricity generated by the fuel cell **305**. Alternatively, the turbine **335** may be used to drive one or more compressors, such as compressors **324, 330,** and **361**. The low pressure carbon dioxide stream may be sequestered or used for carbonation of beverages.

Alternatively, the high pressure carbon dioxide stream may not be converted to a low pressure carbon dioxide stream, and may be used for enhancing oil recovery from an oil formation by injecting the high pressure carbon dioxide stream into the oil formation.

A first gas stream containing hydrogen may be separated from the reformed product gas in the reforming reactor **301** by selectively passing hydrogen through the membrane wall member **323** of the hydrogen separation membrane(s) **303** into the hydrogen conduit **325** of the hydrogen separation membrane(s) **303**. The first gas stream may contain a very high concentration of hydrogen, and may contain at least 0.6, or at least 0.7, or at least 0.8, or at least 0.9, or at least 0.95, or at least 0.98 mole fraction hydrogen.

A sweep gas comprising steam may be injected into the hydrogen conduit **325** via line **337** to sweep hydrogen from the inner portion of the membrane wall member **323**, thereby increasing the rate hydrogen may be separated from the reforming region **315** by the hydrogen separation membrane **303**. The first gas stream and steam sweep gas may be removed from the hydrogen separation membrane **303** and the reforming reactor **301** through hydrogen outlet line **339**.

The first gas stream and the steam sweep gas may be fed to a heat exchanger **341** via hydrogen outlet line **339** to cool the first gas stream and steam sweep gas. The combined first gas stream and steam sweep gas may have a temperature of from 400°C to 650°C, typically a temperature of from 450°C to 550°C, upon exiting the reforming reactor **301**. The combined first gas stream and steam sweep gas may exchange heat with the initial feed precursor and water/steam in the heat exchanger **341**. The initial feed precursor may be provided to the heat exchanger **341** via line **343**, and water/steam may be provided to the heat exchanger **341** via line **345,** where the flow rate of the feed precursor and the water may be regulated by valves **342** and **344**, respectively. The heated feed precursor and steam may fed to heat exchanger **313** via lines **347** and **349**, respectively, for further heating prior to being fed to the pre-reforming reactor **314** as described above. The cooled combined first gas stream and steam sweep gas may be fed to condenser **351** through line **352** to condense water from the combined streams by exchanging heat with water fed into the condenser **351** via line **353** and condensed water separated from the high pressure carbon dioxide gas stream via line **355.**

The water condensed in condenser **351** and water fed to the condenser **351** through lines **353** and **355** may be passed through water trap line **357** to a pump **359** which pumps the water to heat exchanger **329** for heat exchange with the cooled high pressure carbon dioxide gas stream to heat the water while further cooling the cooled high pressure carbon dioxide gas stream. The heated water/steam may be passed to the heat exchanger **341** via line **345**, as described above, for further heating to produce steam to be fed to the pre-reforming reactor **314** after further heating in heat exchanger **313**.

The cooled first gas stream containing hydrogen and little or no water may be fed from the condenser **351** to a compressor **361** through line **363**. The first gas stream may have a pressure at or near atmospheric pressure upon exiting the reforming reactor and being fed through heat exchanger **341** and condenser **351** to the compressor **361**. The first gas stream may be compressed in the compressor **361** to increase the pressure of the first gas stream prior to being fed to the fuel cell **305.** In an embodiment, the first gas stream may be compressed to a pressure of from 0.15 MPa to 0.5 MPa, and preferably from 0.2 MPa to 0.3 MPa. Energy to drive the compressor **361** may be provided by expansion of the high pressure carbon dioxide stream through turbine **335** operatively coupled to drive the compressor **361**.

The first gas stream may then be fed to the anode **307** of the solid oxide fuel cell **305** through line **367** into the anode inlet **365**. The first gas stream provides hydrogen to the anode for electrochemical reaction with an oxidant at one or more anode electrodes along the anode path length in the fuel cell. The rate the first gas stream is fed to the anode **307** of the fuel cell **305** may be selected by selecting the rate that the feed and steam are fed to the reforming reactor **101,** which in turn may be selected by the rate that the feed precursor and water are fed to the pre-reforming reactor **314**, which may be controlled by adjusting metering valves **342** and **344** respectively.

A second gas stream containing hydrogen is also fed to the anode **307** of the fuel cell **305**. The second gas stream may be separated from the anode exhaust stream, which contains hydrogen and water. The second gas stream may be separated from the anode exhaust stream by cooling the anode exhaust stream sufficiently to condense water from the anode gas exhaust stream to produce the second gas stream containing hydrogen.

The anode exhaust stream may be initially cooled by exchanging heat with steam and feed precursor in the pre-reforming reactor **314**, and/or by exchanging heat with steam and a feed in the reforming reactor **301**. The anode exhaust stream exits the anode **307** through the anode exhaust outlet **369**.

In an embodiment, the anode exhaust stream may be fed through line **373** to one or more reformer anode exhaust conduits **319** extending into and located within the reforming region **315** of the reforming reactor **305**. Heat may be exchanged between the anode exhaust stream and the feed and steam in the reforming region **315** of the reforming reactor **301** as the anode exhaust stream passes through the reforming region **315** in the reformer anode exhaust conduit **319**, as described in further detail below, cooling the anode exhaust stream and heating the steam and feed in the reactor **301**.

In an embodiment, the anode exhaust stream may be initially cooled by being fed through line **372** to one or more pre-reformer anode exhaust conduits **320** extending into and located within the pre-reforming region **316** of the pre-reforming reactor **314**. Heat may be exchanged between the anode exhaust stream and a feed precursor and steam in the pre-reforming region **316** of the pre-reforming reactor **314** as the anode exhaust stream passes through the pre-reforming region **316** in the pre-reformer anode exhaust conduit **320**, as described in further detail below, cooling the anode exhaust stream and heating steam and feed precursor in the pre-reforming reactor.

In an embodiment, the anode exhaust stream may be initially cooled by being fed to both the reforming reactor **301** and a pre-reforming reactor **314** through the reformer anode exhaust conduit **319** and through the pre-reformer anode exhaust conduit **320,** respectively, as described above. A portion of the anode exhaust stream may be cooled in the reforming reactor **301** by exchanging heat with feed and steam in the reforming region **315** of the reforming reactor **301** as the anode exhaust passes through the reforming region **315** in the reformer anode exhaust conduit **319**. The rest of the anode exhaust may be cooled in the pre-reforming reactor **314** by exchanging heat with the feed precursor and steam in the pre-reforming region **316** of the pre-reforming reactor **314** as the anode exhaust passes through the pre-reforming region in the pre-reformer anode exhaust conduit **320**.

In another embodiment, the anode exhaust stream may be initially cooled by being fed first to the pre-reforming reactor **314**, then being fed from the pre-reforming reactor to the reforming reactor **301**. The anode exhaust stream may be fed from the anode exhaust outlet **369** to the pre-reformer anode exhaust conduit **320** to be cooled by exchanging heat with the feed precursor and steam in the pre-reforming region **316** of the pre-reforming reactor **314**. The anode exhaust stream may then be fed from the pre-reformer anode exhaust conduit **320** to the reforming reactor **301** via line **374**, where the anode exhaust stream may be fed to the reformer anode exhaust conduit **319** for further cooling by exchanging heat with feed and steam in the reforming region **315** of the reforming reactor **301** as the anode exhaust stream passes through the reformer anode exhaust conduit **319**. Cooling the anode exhaust stream first by exchanging heat in the pre-reforming reactor **314** with the feed precursor and steam and subsequently by exchanging heat in the reforming reactor **301** with the feed and steam may be particularly effective for driving the respective pre-reforming and reforming reactions since the pre-reforming reaction requires more heat than the reforming reaction, and the reforming reaction may be run at a cooler temperature than the pre-reforming reaction to avoid heat damage to the high temperature hydrogen separation membrane **303** located in the reforming region **315** of the reforming reactor **301**

Metering valves **370** and **371** may be used to control the amount of anode exhaust stream directed to the reforming reactor **301** and/or the pre-reforming reactor **314**. The metering valves **370** and **371** may be adjusted to select the flow of the anode exhaust stream either to the reforming reactor **301** or to the pre-reforming reactor **314**. Valve **368** may be used to control the flow of the anode exhaust stream from the pre-reformer anode exhaust conduit **320** to the reformer anode exhaust conduit **319** or from the pre-reformer anode exhaust conduit **320** to be combined with the cooled anode exhaust stream exiting the reformer anode exhaust conduit **319** as described below.

The cooled anode exhaust stream exits the reformer anode exhaust conduit **319** and/or the pre-reformer anode exhaust conduit **320** and may be cooled further to separate the second gas stream containing hydrogen from water in the anode exhaust stream. If any cooled anode exhaust stream exiting the pre-reforming reactor **314** is not passed to the reformer anode exhaust conduit **319** for further heat exchange in the reforming reactor **301**, the cooled anode exhaust stream from the pre-reforming reactor **314** may be passed to heat exchanger **341** for further cooling through line **378**. If any cooled anode exhaust stream exits the reforming reactor **301**, the cooled anode exhaust stream may be passed to heat exchanger **341** through line **382** for further cooling. Cooled anode exhaust streams exiting both the reforming reactor **301** and the pre-reforming reactor **314** may be combined in line **382** and passed to heat exchanger **341** for further cooling.

In one embodiment, to control the flow rate of the second gas stream to the fuel cell **305,** a portion of the anode exhaust stream may be passed to heat exchanger **341** via line **382** to further cool the selected portion of the anode exhaust stream by exchange of heat with the feed precursor from line **343** and steam from line **345**, then fed to a condenser **375** via line **376** to further cool the selected portion of the anode exhaust stream. Hydrogen may be separated from the selected portion of the anode exhaust stream by condensing water from the anode exhaust stream in the condenser **375**. The separated hydrogen may be fed to a hydrogen storage tank **377** through line **379**. Water condensed from condenser **375** may be fed to pump **359** through line **380**.

Cooled anode exhaust stream not fed to condenser **375** for separation into the hydrogen tank is used to provide the second gas stream to the fuel cell **305**. The cooled anode exhaust stream may be passed to heat exchanger **341** via line **382** to further cool the anode exhaust stream by exchange of heat with the feed precursor from line **343** and steam from line **345**, then mixed with the first gas stream and steam sweep gas by feeding the anode exhaust stream through line **381** to line **352**. The mixture of anode exhaust stream, first gas stream, and steam sweep gas may be then fed to condenser **351** to further cool the anode exhaust stream. The second gas stream, derived from condensing water from the anode exhaust stream, may be separated from the condenser **351** via line **363** mixed together with the first gas stream. The second gas stream may contain at least 0.6, or at least 0.7, or at least 0.8, or at least 0.9, or at least 0.95, or at least 0.98 mole fraction hydrogen, where the hydrogen content of the second gas stream may be determined by determining the hydrogen content of the cooled anode exhaust stream on a dry basis. Water from the anode exhaust stream may be condensed in condenser **351** together with water from the first gas stream and the steam sweep gas, and removed from the condenser **351** through line **357** to be fed to pump **359**.

Metering valves **383** and **385** may be used to select the rate of flow of the second gas stream to the solid oxide fuel cell **305**. In order to block the flow of a second gas stream to the fuel cell and to store hydrogen in the hydrogen tank **377**, valve **385** may be completely closed, blocking flow of the anode exhaust stream to the condenser **351** and the second gas stream to the solid oxide fuel cell while valve **383** may be completely opened to allow the anode exhaust stream to flow to condenser **375** and hydrogen to the hydrogen tank **377**. Alternatively, valve **383** may be completely closed, blocking flow of the anode exhaust stream to condenser **375** and hydrogen to the hydrogen tank **377**, and valve **385** may be completely opened to allow the entire anode exhaust stream to flow to the condenser **351** and the second gas stream to flow to the solid oxide fuel cell **305** at a maximum flow rate. The flow rate of the second gas stream to the solid oxide fuel cell may be selected by adjusting valves **383** and **385** in coordination to meter the flow rate of the anode exhaust stream to condenser **351** and the rate of the second gas stream to the solid oxide fuel cell **305**. In a preferred embodiment, the flow rate of the second gas stream to the fuel cell **305** may be automatically controlled to a selected rate by automatically adjusting the metering valves **383** and **385** in response to the water and/or hydrogen content of the anode exhaust stream.

In an embodiment, when the first and second gas streams are combined by adjusting valves **383** and **385** as described above, a small portion of the combined first and second gas streams may be passed through a hydrogen separation device **387** as a bleed stream to remove any small amounts of carbon oxides that may be present in the combined first and second gas stream as a result of imperfect separation of hydrogen from carbon oxides by the hydrogen separation membrane **303** in the reforming reactor **301** when producing the first gas stream and its subsequent recycle in the second gas stream. Valves **389** and **391** may be utilized to control the flow of the bleed stream to the hydrogen separation device **387**, where preferably valves **389** and **391** may permit a metered flow of the combined first and second gas streams simultaneously through lines **393** and **395**, or, alternatively, separately through either line **393** or line **395**. The hydrogen separation device **387** is preferably a pressure swing adsorption apparatus effective for separating hydrogen from carbon oxides, or may be a membrane selectively permeable to hydrogen such as those described above. The first and second gas streams in lines **395** and **397** may be combined to be fed to the solid oxide fuel cell **305** through line **367**.

In an embodiment of the process, the temperature of the first gas stream or the combined first and second gas streams and pressure of the first gas stream or the combined first and second gas streams may be selected for effective operation of the solid oxide fuel cell **305**. In particular, the temperature should not be so low as to inhibit the electrochemical reactivity of the fuel cell and should not be so high as to induce an uncontrolled exothermic reaction in the fuel cell **305**. In an embodiment, the temperature of the first gas stream or the combined first and second gas streams may range from 25°C to 300°C, or from 50°C to 200°C, or from 75°C to 150°C. The pressure of the first gas stream or the combined first and second streams may be controlled by the compression provided to the combined first and second gas streams by compressor **361**, and may be from 0.15 MPa to 0.5 MPa, or from 0.2 MPa to 0.3 MPa.

An oxygen containing gas stream may be fed to the cathode **399** of the fuel cell through cathode inlet **401** via line **403**. The oxygen containing gas stream may be provided by an air compressor or an oxygen tank (not shown). In an embodiment, the oxygen containing gas stream may be air or pure oxygen. In another embodiment, the oxygen containing gas stream may be an oxygen enriched air stream containing at least 21% oxygen, where the oxygen enriched air stream provides higher electrical efficiency in the solid oxide fuel cell than air since the oxygen enriched air stream contains more oxygen for conversion into ionic oxygen in the fuel cell.

The oxygen containing gas stream may be heated prior to being fed to the cathode **399** of the fuel cell **305**. In one embodiment, the oxygen containing gas stream may be heated to a temperature of from 150°C to 350°C prior to being fed to the cathode **399** of the fuel cell **305** in heat exchanger **405** by exchanging heat with a portion of the cathode exhaust provided to the heat exchanger from the cathode exhaust outlet **407** via line **409**. The flow rate of the cathode exhaust stream to the heat exchanger **405** may be controlled with metering valve **411**. Alternatively, the oxygen containing gas stream may be heated by an electrical heater (not shown), or the oxygen containing gas stream may be provided to the cathode **399** of the fuel cell **305** without heating.

The solid oxide fuel cell **305** used in this embodiment of the process of the invention may be a conventional solid oxide fuel cell, preferably having a planar or tubular configuration, and is comprised of an anode **307**, a cathode **399**, and an electrolyte **413** where the electrolyte **413** is interposed between the anode **307** and the cathode **399**. The solid oxide fuel cell may be comprised of a plurality of individual fuel cells stacked together—joined electrically by interconnects and operatively connected so that a fuel may flow through the anodes of the stacked fuel cells and an oxygen containing gas may flow through the cathodes of the stacked fuel cells. The solid oxide fuel cell **305** may be either a single solid oxide fuel cell or a plurality of operatively connected or stacked solid oxide fuel cells. In an embodiment, the anode **307** is formed of a Ni/ZrO_2 cermet, the cathode **399** is formed of a doped lanthanum manganite or stabilized ZrO_2 impregnated with praseodymium oxide and covered with SnO doped In_2O_3, and the electrolyte **413** is formed of yttria stabilized ZrO_2 (approximately 8 mol% Y_2O_3). The interconnect between stacked individual fuel cells or tubular fuel cells may be a doped lanthanum chromite.

The solid oxide fuel cell **305** is configured so that the first gas stream or the combined first and second gas streams may flow through the anode **307** of the fuel cell **305** from the anode inlet **365** to the anode exhaust outlet **369**, contacting one or more anode electrodes over the anode path length from the anode inlet **365** to the anode exhaust outlet **369**. The fuel cell **305** is also configured so that the oxygen containing gas may flow through the cathode **399** from the cathode inlet **401** to the cathode exhaust outlet **407**, contacting one or more cathode electrodes over the cathode path length from the cathode inlet **401** to the cathode exhaust outlet **407**. The electrolyte **413** is positioned in the fuel cell **305** to prevent the first and second gas streams from entering the cathode and to prevent the oxygen containing gas from entering the anode, and to conduct ionic oxygen from the cathode to the anode for electrochemical reaction with hydrogen in the first gas stream or the combined first and second gas streams at the one or more anode electrodes.

The solid oxide fuel cell **305** is operated at a temperature effective to enable ionic oxygen to traverse the electrolyte **413** from the cathode **399** to the anode **307** of the fuel cell **305**. The solid oxide fuel cell **305** may be operated at a temperature of from 700°C to 1100°C, or from 800°C to 1000°C. The oxidation of hydrogen with ionic oxygen at the one or more anode electrodes is a very exothermic reaction, and the heat of reaction generates the heat required to operate the solid oxide fuel cell **305**. The temperature at which the solid oxide fuel cell is operated may be controlled by independently controlling the temperature of the first gas stream, the temperature of the second gas stream fed to the fuel cell (if any), and the oxygen containing gas stream, and the flow rates of these streams to the fuel cell **305**. In an embodiment, the temperature of the second gas stream fed to the fuel cell is controlled to a temperature of at most 100°C, the temperature of the oxygen containing gas stream is controlled to a temperature of at most 300°C, and the temperature of the first gas stream is controlled to a temperature of at most 550°C to maintain the operating temperature of the solid oxide fuel cell in a range from 700°C to 1000°C, and preferably in a range of from 800°C to 900°C.

To initiate operation of the fuel cell **305**, the fuel cell **305** is heated to its operating temperature. In a preferred embodiment, operation of the solid oxide fuel cell **305** may be initiated by generating a hydrogen containing gas stream in a catalytic partial oxidation reforming reactor **433** and feeding the hydrogen containing gas stream through line **435** to the anode **307** of the solid oxide fuel cell. A hydrogen containing gas stream may be generated in the catalytic partial oxidation reforming reactor **433** by combusting a hydrocarbon feed and an oxygen source in the catalytic partial oxidation reforming reactor **433** in the presence of a conventional partial oxidation reforming catalyst, where the oxygen source is fed to the catalytic partial oxidation reforming reactor **433** in a substoichiometric amount relative to the hydrocarbon feed.

The hydrocarbon feed fed to the catalytic partial oxidation reforming reactor **433** may be a liquid or gaseous hydrocarbon or mixtures of hydrocarbons, and preferably is methane, natural gas, or other low molecular weight hydrocarbon or mixture of low molecular weight hydrocarbons. In a particularly preferred embodiment of the process of the invention, the hydrocarbon feed fed to the catalytic partial oxidation reforming reactor **433** may a feed of the same type as the feed precursor used in the pre-reforming reactor **314** to reduce the number of hydrocarbon feeds required run the process.

The oxygen containing feed fed to the catalytic partial oxidation reforming reactor **433** may be pure oxygen, air, or oxygen enriched air. The oxygen containing feed should be fed to the catalytic partial oxidation reforming reactor **433** in substoichiometric amounts relative to the hydrocarbon feed to combust with the hydrocarbon feed in the catalytic partial oxidation reforming reactor **433**.

The hydrogen containing gas stream formed by combustion of the hydrocarbon feed and the oxygen containing gas in the catalytic partial oxidation reforming reactor **433** contains compounds that may be oxidized in the anode **307** of the fuel cell **305** by contact with an oxidant at one or more of the anode electrodes, including hydrogen and carbon monoxide, as well as other compounds such as carbon dioxide. The hydrogen containing gas steam from the catalytic partial oxidation reforming reactor **433** preferably does not contain compounds that may oxidize the one or more anode electrodes in the anode **307** of the fuel cell **305**.

The hydrogen containing gas stream formed in the catalytic partial oxidation reforming reactor **433** is hot, and may have a temperature of at least 700°C, or from 700°C to 1100°C, or from 800°C to 1000°C. Use of the hot hydrogen gas stream from a catalytic partial oxidation reforming reactor **433** to initiate start up of the solid oxide fuel cell **305** is preferred in the process of the invention since it enables the temperature of the fuel cell **305** to be raised to the operating temperature of the fuel cell **305** almost instantaneously. In an embodiment, heat may be exchanged in heat exchanger **405** between the hot hydrogen containing gas from the catalytic partial oxidation reforming reactor **433** and an oxygen containing gas fed to the cathode **399** of the fuel cell **305** when initiating operation of the fuel cell **305**.

Upon reaching the operating temperature of the fuel cell **305**, the flow of the hot hydrogen containing gas stream from the catalytic partial oxidation reforming reactor **433** into the fuel cell **305** may be shut off by valve **439**, while feeding the first gas stream from the reforming reactor **301**into the anode **307** by opening valve **441** and feeding the oxygen containing gas stream into the cathode **399** of the fuel cell **305**. Continuous operation of the fuel cell may then conducted according to the process of the invention.

In another embodiment, operation of the fuel cell **305** may be initiated with a hydrogen start-up gas stream from a hydrogen storage tank (not shown) that may be passed through a start-up heater (not shown) to bring the fuel cell **305** up to its operating temperature prior to introducing the first gas stream into the fuel cell **305**. The hydrogen storage tank may be operatively connected to the fuel cell **305** to permit introduction of the hydrogen start-up gas stream into the anode **307** of the solid oxide fuel cell **305**. The start-up heater may indirectly heat the hydrogen start-up gas stream to a temperature of from 750°C to 1000°C. The start-up heater may be an electrical heater or may be a combustion heater. Upon reaching the operating temperature of the fuel cell **305**, the flow of the hydrogen start-up gas stream into the fuel cell **305** may be shut off by a valve (not shown), and the first gas stream and the oxygen containing gas stream may be introduced into the fuel cell **305** to start the operation of the fuel cell.

During initiation of operation of the fuel cell **305,** a oxygen containing gas stream may be introduced into the cathode **399** of the fuel cell **305**. The oxygen containing gas stream may be air, oxygen enriched air containing at least 21% oxygen, or pure oxygen. Preferably, the oxygen containing gas stream may be the oxygen containing gas stream that will be fed to the cathode **399** during operation of the fuel cell **305** during operation of the fuel cell **305** after initiating operation of the fuel cell.

In a preferred embodiment, the oxygen containing gas stream fed to the cathode **399** of the fuel cell during start-up of the fuel cell has a temperature of at least 500°C, more preferably at least 650°C, and more preferably at least 750°C. The oxygen containing gas stream may be heated by an electric heater before being fed to the cathode **399** of the solid oxide fuel cell **305**. In a preferred embodiment, the oxygen containing gas stream used in initiating operation of the fuel cell **305** may be heated by heat exchange with a hot hydrogen containing gas stream from a catalytic partial oxidation reforming reaction in heat exchanger **405** prior to being fed to the cathode **399** of the fuel cell **305**.

Once operation of the fuel cell has commenced, the first gas stream or the combined first and second gas streams may be mixed with an ionic oxygen oxidant at one or more anode electrodes in the fuel cell **305** to generate electricity. The ionic oxygen oxidant is derived from oxygen in the oxygen-containing gas stream flowing through the cathode **399** of the fuel cell **305** and conducted across the electrolyte **413** of the fuel cell. The first gas stream or the combined first and second gas streams fed to the anode **307** of the fuel cell **305** and the oxidant are mixed in the anode **307** at the one or more anode electrodes of the fuel cell **305** by feeding the first gas stream, the second gas stream (if any), and the oxygen containing gas stream to the fuel cell **305** at selected independent rates while operating the fuel cell at a temperature of from 750°C to 1100°C.

The first gas stream or the combined first and second gas streams and the oxidant are preferably mixed at the one or more anode electrodes of the fuel cell **305** to generate electricity at an electrical power density of at least 0.4 W/cm^2, more preferably at least 0.5 W/cm^2, or at least 0.75 W/cm^2, or at least 1 W/cm^2, or at least 1.25 W/cm^2, or at least 1.5 W/cm^2. Electricity may be generated at such electrical power densities by selecting and controlling the rate that the first gas stream is fed to the anode **307** of the fuel cell **305** or independently selecting and controlling the flow rates of the first gas stream and the second gas stream to the anode **307** of the fuel cell **305**. The flow rate of the first gas stream to the anode **307** of the fuel cell **305** may be selected and controlled by selecting and controlling the rate that the feed and steam are fed to the reforming reactor **301**, which in turn is controlled by the rate that the feed precursor and steam are fed to the pre-reforming reactor **314**, which is controlled by adjusting metering valves **342** and **344**, respectively. The flow rate of the second gas stream to the anode **307** of the fuel cell **305** may be selected and controlled by selecting and controlling the flow rate of the anode exhaust stream to the condenser **351** by adjusting metering valves **383** and **385** as described above. In an embodiment, metering valves **383** and **385** may be automatically adjusted by a feedback circuit (not shown) that measures water and/or hydrogen content in the anode exhaust stream, and adjusts the metering valves **383** and **385** to maintain a selected water and/or hydrogen content in the anode exhaust stream.

In the process of the invention, mixing the first gas stream or the combined first and second gas streams and the oxidant at the one or more anode electrodes generates water (as steam) by the oxidation of a portion of hydrogen present in the first gas stream or the combined first and second gas streams fed to the fuel cell **305** with the oxidant. Water generated by the oxidation of hydrogen with an oxidant is swept through the anode **307** of the fuel cell **305** by the unreacted portion of the first gas stream or the combined first and second gas streams to exit the anode **307** as part of the anode exhaust stream.

In an embodiment of the process of the invention, the flow rate that the first gas stream is fed to the anode **307** and, if a second gas stream is provided to the anode **307**, the flow rate that the second gas stream is fed to the anode **307** may be independently selected so the ratio of amount of water formed in the fuel cell **305** per unit of time to the amount of hydrogen in the anode exhaust per unit of time is at most 1.0, or at most 0.75, or at most 0.67, or at most 0.43, or at most 0.25, or at most 0.11. In an embodiment, the amount of water formed in the fuel cell **305** and the amount of hydrogen in the anode exhaust may be measured in moles so that the ratio of the amount of water formed in the fuel cell per unit of time to the amount of hydrogen in the anode exhaust per unit of time in moles per unit of time is at most 1.0, or at most 0.75, or at most 0.67, or at most 0.43, or at most 0.25, or at most 0.11. In another embodiment of the process of the invention, the flow rate that the first gas stream is fed to the anode **307** and, if a second gas stream is provided to the anode **307**, the flow rate that the second gas stream is fed to the anode **307,** may be independently selected so the anode exhaust stream contains at least 0.6, or at least 0.7, or at least 0.8, or at least 0.9 mole fraction hydrogen. In an embodiment, the flow rate that the first gas stream is fed to the anode **307** and, if a second gas stream is provided to the anode, the flow rate that the second gas stream is fed to the anode **307** may be independently selected so the anode exhaust stream contains at least 50%, or at least 60%, or at least 70%, or at least 80%, or at least 90% of the hydrogen in the combined first and second gas streams fed to the anode **307,** or, if only the first gas stream is provided to the anode **307**, the anode exhaust stream contains at least 50%, or at least 60%, or at least 70%, or at least 80%, or at least 90% of the hydrogen in the first gas stream provided to the anode **307**. . In an embodiment, the flow rate that the first gas stream is fed to the anode **307** and, if a second gas stream is provided to the anode, the flow rate that the second gas stream is fed to the anode **307** may be independently selected so the per pass hydrogen utilization rate in the fuel cell **305** is at most 50%, or at most 40%, or at most 30%, or at most 20%, or at most 10%.

The flow rate of the oxygen containing gas stream provided to the cathode **399** of the solid oxide fuel cell **305** should be selected to provide sufficient oxidant to the anode to generate electricity at an electrical power density of at least 0.4 W/cm^2, or at least 0.5 W/cm^2, or at least 0.75 W/cm^2, or at least 1 W/cm^2, or at least 1.25 W/cm^2, or at least 1.5 W/cm^2 when combined with the fuel from the first gas stream or the combined first and second gas streams at the one or more anode electrodes. The flow rate of the oxygen containing gas stream to the cathode **399** may be selected and controlled by adjusting metering valve **415**.

In one embodiment of the process of the present invention, the reforming reactor **301** and the solid oxide fuel cell **305** may be thermally integrated so the heat from the exothermic electrochemical reaction in the fuel cell **305** is provided to the reforming region **315** of the reforming reactor **301** to drive the endothermic reforming reaction in the reforming reactor **301**. As described above, one or more reformer anode exhaust conduits **319** and/or one or more reformer cathode exhaust conduits **317** extend into and are located within the reforming region **315** of the reforming reactor **301**. A hot anode exhaust stream may exit the anode **307** of the fuel cell **305** from the anode exhaust outlet **369** and enter the reformer anode exhaust conduit **319** in the reforming region **315** via line **373**, and/or a hot cathode exhaust stream may exit the cathode **399** of the fuel cell **305** from the cathode exhaust outlet **407** and enter the reformer cathode exhaust conduit **317** in the reforming region **315** via line **417**. Heat from the hot anode exhaust stream may be exchanged between the anode exhaust stream and the mixture of steam and feed in the reforming region **315** as the anode exhaust stream passes through the reformer anode exhaust conduit

319. Likewise, heat from the hot cathode exhaust stream may be exchanged between the cathode exhaust stream and the mixture of steam and feed in the reforming region **315** of the reforming reactor **301** as the cathode exhaust stream passes through the reformer cathode exhaust conduit **317**.

The heat exchange from the exothermic solid oxide fuel cell **305** to the endothermic reforming reactor **301** is highly efficient. Location of the reformer anode exhaust conduit(s) **319** and/or the reformer cathode exhaust conduit(s) **317** within the reforming region **315** of the reforming reactor **301** permits exchange of heat between the hot anode and cathode exhaust streams and the mixture of feed and steam within the reactor **301**, transferring heat to the feed and steam at the location that the reforming reaction takes place. Further, location of the reformer anode and/or cathode exhaust conduits **319** and **317** within the reforming region **315** permits the hot anode and/or cathode exhaust streams to heat the reforming catalyst in the reforming region **315** as a result of the close proximity of the conduits **317** and **319** to the catalyst bed.

Further, no additional heat other than provided by the anode exhaust stream and/or the cathode exhaust stream needs to be provided to the reforming reactor **301** to drive the reforming and shift reactions in the reactor **301** to produce the reformed product gas and the first gas stream. As noted above, the temperature required to run the reforming and shift reactions within the reforming reactor **301** is from 400°C to 650°C, which is much lower than conventional reforming reactor temperatures—which are at least 750°C, and typically 800°C-900°C. The reforming reactor may be run at such low temperatures due to the equilibrium shift in the reforming reaction engendered by separation of hydrogen from the reforming reactor **301** by the high temperature hydrogen separation membrane **303**. The anode exhaust stream and the cathode exhaust stream may have a temperature of from 800°C to 1000°C, which, upon heat exchange between the anode exhaust stream and/or the cathode exhaust stream with the mixture of feed and steam, is sufficient to drive the lower temperature reforming and shift reactions in the reforming reactor **301**.

In an embodiment of the process of the invention, the exchange of heat between the anode exhaust stream and the mixture of steam and feed in the reforming region **315** as the anode exhaust stream passes through the reformer anode exhaust conduit **319** may provide a significant amount of the heat provided to the mixture of steam and feed in the reactor **301** to drive the reforming and shift reactions. In an embodiment of the process of the invention, the exchange of heat between the anode exhaust stream and the mixture of steam and feed in the reactor **301** may provide at least 40%, or at least 50%, or at least 70%, or at least 90% of the heat provided to the mixture of steam and feed in the reactor **301**. In an embodiment, the heat supplied to the mixture of steam and feed in the reforming reactor **301** consists essentially of the heat exchanged between the anode exhaust stream passing through the reformer anode exhaust conduit **319** and the mixture of steam and feed in the reforming reactor **301**. In an embodiment of the process, the exchange of heat between the anode exhaust stream and the mixture of steam and feed in the reactor **301** may be controlled to maintain the temperature of the mixture of steam and feed in a range of from 400°C to 650°C.

In an embodiment of the process of the invention, the exchange of heat between the cathode exhaust stream and the mixture of steam and feed in the reforming region **315** as the cathode exhaust stream passes through the reformer cathode exhaust conduit **317** may provide a significant amount of the heat provided to the mixture of steam and feed in the reactor **301** to drive the reforming and shift reactions. In an embodiment of the process of the invention, the exchange of heat between the cathode exhaust stream and the mixture of steam and feed in the reactor **301** may provide at least 40%, or at least 50%, or at least 70%, or at least 90% of the heat provided to the mixture of steam and feed in the reactor **301**. In an embodiment, the heat supplied to the mixture of steam and feed in the reforming reactor **301** consists essentially of the heat exchanged between the cathode exhaust stream passing through the reformer cathode exhaust conduit **317** and the mixture of steam and feed in the reforming reactor **301**. In an embodiment of the process, the exchange of heat between the cathode exhaust stream and the mixture of steam and feed in the reactor **301** may be controlled to maintain the temperature of the mixture of steam and feed in a range of from 400°C to 650°C.

In an embodiment, the exchange of heat between the anode exhaust stream, the cathode exhaust stream, and the mixture of steam and feed in the reforming region **315** as the anode exhaust stream passes through the reformer anode exhaust conduit **319** and the cathode exhaust stream passes through the reformer cathode exhaust conduit **317** may provide a significant amount of the heat provided to the mixture of steam and feed in the reactor **301** to drive the reforming and shift reactions. In an embodiment of the process of the invention, the exchange of heat between the cathode exhaust stream and the mixture of steam and feed in the reactor **301** may provide up to 60%, or up to 50%, or up to 40%, or up to 30%, or up to 20% of the heat provided to the mixture of steam and feed in the reactor **301** while the exchange of heat between the anode exhaust stream and the mixture of steam and feed in the reactor **301** may provide at least 40%, or at least 50%, or at least 60%, or at least 70%, or at least 80% of the heat provided to the mixture of steam and feed in the reactor **301**. In an embodiment, the heat supplied to the mixture of steam and feed in the reforming reactor **301** may consist essentially of heat exchanged between the anode and cathode exhaust streams and the mixture of steam and feed in the reactor **301**. In an embodiment of the process, the exchange of heat between the anode and cathode exhaust streams and the mixture of steam and feed in the reactor **301** may be controlled to maintain the temperature of the mixture of steam and feed in a range of from 400°C to 650°C.

In a preferred embodiment, the heat provided by the anode exhaust stream or the cathode exhaust stream or the anode and cathode exhaust streams to the mixture of steam and feed in the reforming reactor **301** is sufficient to drive the reforming and shift reactions in the reforming reactor **301** such that no other source of heat is required to drive the reactions in the reforming reactor **301**. Most preferably, no heat is provided to the mixture of steam and feed in the reforming reactor **301** by electrical heating or combustion.

In an embodiment, the anode exhaust stream provides most, or all, of the heat to the mixture of steam and feed in the reforming reactor **301** to drive the reforming and shift reactions in the reactor. Metering valves **371** and **370** may be adjusted to control the flow of the anode exhaust stream from the fuel cell to the reformer anode exhaust conduit **319**, where the flow of the anode exhaust stream through the valve **371** may be increased and its flow through valve **370** may be decreased to increase flow of the anode exhaust stream into the reformer anode exhaust conduit **319** to provide the heat required to drive the reforming and shift reactions in reforming reactor **301**.

In this embodiment only some, or none, of the cathode exhaust stream is required to exchange heat with the mixture of steam and feed in the reforming reactor **301** to drive the reforming and shift reactions. The flow of the cathode exhaust stream through the reforming cathode exhaust conduit **317** in the reforming reactor **301** may be controlled to control the amount of heat provided to the mixture of steam and feed in the reforming reactor **301** from the cathode exhaust stream. Metering valves **411**, **412**, **429**, and **431** may be adjusted to control the flow of the cathode exhaust stream to the reformer cathode exhaust conduit **317** such that the cathode exhaust stream provides the desired amount of heat, if any, to the mixture of steam and feed in the reactor **301**. To decrease the flow of cathode exhaust to the reforming reactor **301** through the reformer cathode exhaust conduit

317, valves **412** and **431** may be adjusted to decrease flow of the cathode exhaust through valves **412** and **431** and valves **411** and **429** may be adjusted to increase flow of the cathode exhaust through valves **411** and **429**.

In an embodiment, the cathode exhaust stream provides most, or all, of the heat to the mixture of steam and feed in the reforming reactor **301** to drive the reforming and shift reactions in the reactor. Metering valves **411**, **412**, **429**, and **431** may be adjusted to control the flow of the cathode exhaust stream to the reformer cathode exhaust conduit **317** such that the cathode exhaust stream provides the desired amount of heat to the mixture of steam and feed in the reactor **301**. To increase the flow of cathode exhaust to the reforming reactor **301** through the reformer cathode exhaust conduit **317**, valves **412** and **431** may be adjusted to increase flow of the cathode exhaust through valves **412** and **431** and valves **411** and **429** may be adjusted to decrease flow of the cathode exhaust through valves **411** and **429**.

In this embodiment only some, or none, of the anode exhaust stream is required to exchange heat with the mixture of steam and feed in the reforming reactor **301** to drive the reforming and shift reactions. The flow of the anode exhaust stream through the reforming anode exhaust conduit **319** in the reforming reactor **301** may be controlled to control the amount of heat provided to the mixture of steam and feed in the reforming reactor **301** from the anode exhaust stream. Metering valves **371** and **370** may be adjusted to control the flow of the anode exhaust stream from the fuel cell **305** to the reformer anode exhaust conduit **319**, where anode exhaust stream flow through the valve **371** may be decreased and its flow through the valve **370** may be increased to decrease flow of the anode exhaust stream into the reformer anode exhaust conduit **319**.

The cooled cathode exhaust stream that has passed through the reformer cathode exhaust conduit **317** may still have a significant amount of heat therein, and may have a temperature of up to 650°C. The cooled cathode exhaust stream may be passed out of the cathode exhaust conduit through outlet **418** to be fed to the oxygen containing gas heat exchanger **405** through line **419** along with any cathode exhaust stream metered to the heat exchanger **405** through valve **411**. The cooled anode exhaust stream that has passed through the reformer anode exhaust conduit **319** is treated as described above to provide the second gas stream to the fuel cell **305**.

In one embodiment of the process of the present invention, the pre-reforming reactor **314** and the solid oxide fuel cell **305** may be thermally integrated so the heat from the exothermic electrochemical reaction in the fuel cell **305** is provided to the pre-reforming region **316** of the pre-reforming reactor **314** to drive the endothermic vaporization and cracking/reforming reactions in the pre-reforming reactor **314**. As described above, one or more pre-reformer anode exhaust conduits **320** and/or one or more pre-reformer cathode exhaust conduits **322** extend into and are located within the pre-reforming region **316** of the pre-reforming reactor **314**. A hot anode exhaust stream may exit the anode **307** of the fuel cell **305** from the anode exhaust outlet **369** and enter the pre-reformer anode exhaust conduit **320** in the pre-reforming region **316** via line **372**, and a hot cathode exhaust stream may exit the cathode **399** of the fuel cell **305** from the cathode exhaust outlet **407** and enter the pre-reformer cathode exhaust conduit **322** in the pre-reforming region **316** via line **421**. Heat from the hot anode exhaust stream may be exchanged between the anode exhaust stream and the mixture of steam and feed precursor in the pre-reforming region **316** as the anode exhaust stream passes through the pre-reformer anode exhaust conduit **320**. Likewise, heat from the hot cathode exhaust stream may be exchanged between the cathode exhaust stream and the mixture of steam and feed precursor in the pre-reforming region **316** of the pre-reforming reactor **314** as the cathode exhaust stream passes through the pre-reformer cathode exhaust conduit **322**.

The heat exchange from the exothermic solid oxide fuel cell **305** to the endothermic pre-reforming reactor **314** is highly efficient. Location of the pre-reformer anode exhaust conduit(s) **320** and/or the pre-reformer cathode exhaust conduit(s) **322** within the pre-reforming region **316** of the pre-reforming reactor **314** permits exchange of heat between the hot anode and/or cathode exhaust streams and the mixture of feed precursor and steam within the reactor **314**, transferring heat to the feed precursor and steam at the location that the vaporization/cracking/reforming reactions take place. Further, location of the pre-reformer anode and/or cathode exhaust conduits **320** and **322** within the pre-reforming region **316** permits the hot anode and/or cathode exhaust streams to heat the pre-reforming catalyst in the pre-reforming region **316** as a result of the close proximity of the conduits **320** and **322** to the catalyst bed.

Further, no additional heat other than provided by the anode exhaust stream and/or the cathode exhaust stream needs to be provided to the pre-reforming reactor **314** to drive the vaporization/cracking/reforming reactions in the pre-reforming reactor **314** to produce the feed for the reforming reactor **301**. The temperature required to crack or reform the feed precursor hydrocarbons to hydrocarbons useful as feed for the reforming reactor may be from 400°C to 850°C, or from 500°C to 800°C, and may be higher than required to reform the feed in the reforming reactor **301.** The anode exhaust stream and the cathode exhaust stream may have a temperature of from 800°C to 1000°C, which, upon heat exchange between the anode exhaust stream and/or the cathode exhaust stream and the mixture of feed precursor and steam, is sufficient to drive the conversion of feed precursors to feed in the pre-reforming reactor **314**.

In an embodiment of the process of the invention, the exchange of heat between the anode exhaust stream and the mixture of steam and feed precursor in the pre-reforming region **316** as the anode exhaust stream passes through the pre-reformer anode exhaust conduit **320** may provide a significant amount of the heat provided to the mixture of steam and feed precursor in the pre-reforming reactor **314** to drive the pre-reforming/cracking reactions. In an embodiment of the process of the invention, the exchange of heat between the anode exhaust stream and the mixture of steam and feed precursor in the pre-reforming reactor **314** may provide at least 40%, or at least 50%, or at least 70%, or at least 90% of the heat provided to the mixture of steam and feed precursor in the pre-reforming reactor **314**. In an embodiment, the heat supplied to the mixture of steam and feed precursor in the pre-reforming reactor **314** consists essentially of the heat exchanged between the anode exhaust stream passing through the pre-reformer anode exhaust conduit **320** and the mixture of steam and feed precursor in the pre-reforming reactor **314**. In an embodiment of the process, the exchange of heat between the anode exhaust stream and the mixture of steam and feed in the pre-reforming reactor **314** may be controlled to maintain the temperature of the mixture of steam and feed precursor in a range of from 500°C to 800°C.

In an embodiment of the process of the invention, the exchange of heat between the cathode exhaust stream and the mixture of steam and feed precursor in the pre-reforming region **316** as the cathode exhaust stream passes through the pre-reformer cathode exhaust conduit **322** may provide a significant amount of the heat provided to the mixture of steam and feed precursor in the pre-reforming reactor **314** to drive the vaporization/cracking/reforming reactions. In an embodiment of the process of the invention, the exchange of heat between the cathode exhaust stream and the mixture of steam and feed precursor in the pre-reforming reactor **314** may provide at least 40%, or at least 50%, or at least 70%, or at least 90% of the heat provided to the mixture of steam and feed precursor in the pre-reforming reactor **314**. In an embodiment, the heat supplied to the mixture of steam and feed precursor in the pre-reforming reactor **314** consists essentially of the heat exchanged between the cathode exhaust stream passing through the pre-reformer anode exhaust conduit **322** and the mixture of steam and feed precursor in the pre-reforming reactor **314**. In an embodiment of the process, the exchange of heat between the cathode exhaust stream and the mixture of steam and feed in the pre-reforming reactor **314** may be controlled to maintain the temperature of the mixture of steam and feed precursor in a range of from 500°C to 800°C.

In an embodiment, the exchange of heat between the anode exhaust stream, the cathode exhaust stream, and the mixture of steam and feed precursor in the pre-reforming region **316** as the anode exhaust stream passes through the pre-reformer anode exhaust conduit **320** and the cathode exhaust stream passes through the pre-reformer cathode exhaust conduit **322** may provide a significant amount of the heat provided to the mixture of steam and feed precursor in the pre-reforming reactor **314** to drive the vaporization/cracking/reforming reactions. In an embodiment of the process of the invention, the exchange of heat between the cathode exhaust stream and the mixture of steam and feed precursor in the reactor **314** may provide up to 60%, or up to 50%, or up to 40%, or up to 30%, or up to 20% of the heat provided to the mixture of steam and feed precursor in the reactor **314** while the exchange of heat between the anode exhaust stream and the mixture of steam and feed precursor may provide at least 40%, or at least 50%, or at least 60%, or at least 70%, or at least 80% of the heat provided to the mixture of steam and feed precursor in the reactor **314**. In an embodiment, the heat supplied to the mixture of steam and feed precursor in the pre-reforming reactor **314** may consist essentially of heat exchanged between the anode and cathode exhaust streams and the mixture of steam and feed precursor in the reactor **314**. In an embodiment of the process, the exchange of heat between the anode and cathode exhaust streams and the mixture of steam and feed precursor in the reactor **314** may be controlled to maintain the temperature of the mixture of steam and feed precursor in a range of from 500°C to 800°C.

In a preferred embodiment, the heat provided by the anode exhaust stream, or the cathode exhaust stream, or the anode and cathode exhaust streams to the mixture of steam and feed precursor in the pre-reforming reactor **314** is sufficient to drive the pre-reforming/cracking reactions in the reforming reactor **314** such that no other source of heat is required to drive the reactions in the pre-reforming reactor **314**. Most preferably, no heat is provided to the mixture of steam and feed precursor in the reactor **314** by electric heat or combustion.

In an embodiment, the anode exhaust stream provides most, or all, of the heat to the mixture of steam and feed precursor in the pre-reforming reactor **314** to drive the vaporization/cracking/reforming reactions in the reactor **314**. Metering valves **371** and **370** may be adjusted to control the flow of the anode exhaust stream from the fuel cell **305** to the pre-reformer anode exhaust conduit **320**, where the flow of the anode exhaust stream through the valve **370** may be increased and its flow through valve **371** may be decreased to increase flow of the anode exhaust stream into the pre-reformer anode exhaust conduit **320** to provide the heat required to drive the vaporization/cracking/reforming reactions in pre-reforming reactor **314**.

In this embodiment only some, or none, of the cathode exhaust stream is required to exchange heat with the mixture of steam and feed precursor in the pre-reforming reactor **314** to drive the vaporization/cracking/reforming reactions. The flow of the cathode exhaust stream through the pre-reforming cathode exhaust conduit **322** in the pre-reforming reactor **314** may be controlled to control the amount of heat provided to the mixture of steam and feed precursor in the pre-reforming reactor **314** from the cathode exhaust stream. Metering valves **411**, **412**, **429**, and **431** may be adjusted to control the flow of the cathode exhaust stream to the pre-reformer cathode exhaust conduit **322** such that the cathode exhaust stream provides the desired amount of heat, if any, to the mixture of steam and feed precursor in the pre-reforming reactor **314**. To decrease the flow of the cathode exhaust stream to the pre-reforming reactor **314** through the pre-reformer cathode exhaust conduit **322**, valves **412** and **429** may be adjusted to decrease flow of the cathode exhaust through valves **412** and **429** and valves **411** and **431** may be adjusted to increase flow of the cathode exhaust through valves **411** and **431**.

Cathode exhaust stream that is not required to heat the mixture of steam and feed in the reforming reactor **301** or pre-reforming reactor **314** may be shunted through line **409** to heat exchanger **405** to heat the oxygen containing gas fed to the cathode **399**.

In an embodiment, the cathode exhaust stream provides most, or all, of the heat to the mixture of steam and feed precursor in the pre-reforming reactor **314** to drive the vaporization/cracking/reforming reactions in the reactor **314**. Metering valves **411**, **412**, **429**, and **431** may be adjusted to control the flow of the cathode exhaust stream to the pre-reformer cathode exhaust conduit **322** such that the cathode exhaust stream provides the desired amount of heat to the mixture of steam and feed precursor in the reactor **314**. To increase the flow of the cathode exhaust stream to the pre-reforming reactor **314** through the pre-reformer cathode exhaust conduit **322**, valves **412** and **429** may be adjusted to increase flow of the cathode exhaust stream through valves **412** and **429** and valves **411** and **431** may be adjusted to decrease flow of the cathode exhaust stream through valves **411** and **431**.

In this embodiment only some, or none, of the anode exhaust stream is required to exchange heat with the mixture of steam and feed precursor in the pre-reforming reactor **314** to drive the vaporization/cracking/reforming reactions. The flow of the anode exhaust stream through the reforming anode exhaust conduit **320** in the pre-reforming reactor **314** may be controlled to control the amount of heat provided to the mixture of steam and feed precursor in the pre-reforming reactor **314** from the anode exhaust stream. Metering valves **371** and **370** may be adjusted to control the flow of the anode exhaust stream from the fuel cell **305** to the pre-reformer anode exhaust conduit **320**, where anode exhaust stream flow through the valve **370** may be decreased and its flow through the valve **371** may be increased to decrease flow of the anode exhaust stream into the pre-reformer anode exhaust conduit **320**.

The cooled cathode exhaust stream that has passed through the pre-reformer cathode exhaust conduit **322** may still have a significant amount of heat therein, and may have a temperature of up to 800°C. The cooled cathode exhaust stream may be passed out of the cathode exhaust conduit through outlet **423** to be fed to the oxygen containing gas heat exchanger **405** through line **419** along with any cathode exhaust stream metered to the heat exchanger **405** through valve **411**.

In a preferred embodiment, the reforming reactor **301**, the pre-reforming reactor **314**, and the solid oxide fuel cell **305** may be thermally integrated so the heat from the exothermic electrochemical reaction in the fuel cell **305** is provided to both the reforming region **315** of the reforming reactor **301**, to drive the endothermic reforming reaction in the reforming reactor **301**, and the pre-reforming region **316** of the pre-reforming reactor **314** to drive the endothermic vaporization/cracking/reforming reactions. The fuel cell **305** may be operatively connected to the reforming reactor **301** and the pre-reforming reactor **314** as described above.

In an embodiment, the pre-reforming anode exhaust conduit(s) **320** may be operatively connected in series with the reforming anode exhaust conduit(s) **319** so that the anode exhaust stream may flow from the anode exhaust outlet **369** of the fuel cell **305** through the pre-reforming reactor **314**, then through the reforming reactor **301**. Flow of the anode exhaust stream from the pre-reformer anode exhaust conduit(s) **320** to the reformer anode exhaust conduit(s) **319** may be controlled by adjusting valve **368**.

In an embodiment, the pre-reforming cathode exhaust conduit(s) **322** of the pre-reforming reactor **314** may be operatively connected in series with the reforming cathode exhaust conduit(s) **317** of the reforming reactor **301** so that the cathode exhaust stream may flow from the cathode exhaust outlet **407** through the pre-reforming reactor **314**, then through line **425** into the reformer cathode exhaust conduit **317** of the reforming reactor **301.** Flow of the cathode exhaust stream from the pre-reforming reactor **314** into the reforming reactor **301** through line **425** may be controlled by adjusting valve **427**.

In another embodiment, the pre-reformer anode exhaust conduit(s) **320** and the reformer anode exhaust conduit(s) **319** may be operatively connected in parallel so the anode exhaust stream may flow from the anode exhaust outlet **365** simultaneously through both the pre-reformer anode exhaust conduit(s) **320** and the reformer anode exhaust conduit(s) **319.** Metering valves **371** and **370** may be adjusted so that the anode exhaust stream flows into the reformer anode exhaust conduit(s) **319** and the pre-reformer anode exhaust conduit(s) **320**, respectively, at desired rates.

In another embodiment, the pre-reformer cathode exhaust conduit(s) **322** may be operatively connected in parallel with the reformer cathode exhaust conduit(s) **317** so the cathode exhaust stream may flow from the cathode exhaust outlet **407** through the pre-reformer cathode exhaust conduit(s) **422** and the reformer cathode exhaust conduit(s) **417** simultaneously. Metering valves **431** and **429** may be adjusted so that the cathode exhaust stream flows into the reformer cathode exhaust conduit(s) **317** and the pre-reformer cathode exhaust conduit(s) **322**, respectively, at desired rates.

The flow of the anode exhaust stream through the pre-reforming reactor **314** and the reforming reactor **301** to provide heat to the reactors **301** and **314** may be controlled by metering valves **370**, **371**, and **376.** Metering valve **370** may be used to control the flow of the anode exhaust stream from the anode exhaust outlet **365** to the pre-reformer anode exhaust conduit(s) **320**. Metering valve **371** may be used to control the flow of the anode exhaust stream from the anode exhaust outlet **365** to the reformer anode exhaust conduit(s) **319**. Metering valve **376** may be used to control the flow of the anode exhaust stream from the pre-reformer anode exhaust conduit **320** so that the anode exhaust stream may be directed into the reformer anode exhaust conduit **319**.

The flow of the cathode exhaust stream through the pre-reforming reactor **314** and the reforming reactor **301** to provide heat to the reactors **301** and **314** may be controlled by metering valves **412**, **427**, **429,** and **431**. Metering valve **412** may be used to control the flow of the cathode exhaust stream from the fuel cell cathode exhaust outlet to the pre-reforming reactor **314** and the reforming reactor **301**. Metering valve **429** may be used to control the flow of the cathode exhaust stream from the cathode exhaust outlet **407** to the pre-reformer cathode exhaust conduit(s) **322**. Metering valve **431** may be used to control the flow of the cathode exhaust stream from the cathode exhaust outlet **407** to the reformer cathode exhaust conduit(s) **317**. Metering valve **427** may be used to control the flow of the cathode exhaust stream from the pre-reformer cathode exhaust conduit **322** so that the cathode exhaust stream may be directed into the reformer cathode exhaust conduit **317**.

In this embodiment of the process of the present invention, relatively little carbon dioxide is generated per unit of electricity produced by the process. The thermal integration of the reforming reactor **301** and, optionally the pre-reforming reactor **314**, with the fuel cell **305**—wherein the heat produced in the fuel cell **305** is transferred within the reforming reactor **301**, and optionally within the pre-reforming reactor **314** by the anode and/or cathode exhausts from the fuel cell **305**—reduces the energy required to be provided to drive the endothermic reforming and pre-reforming reactions, reducing the need to provide such energy, for example by combustion, thereby reducing the amount of carbon dioxide produced in providing energy to drive the reforming reaction. Additionally, where the second gas stream is separated from the anode exhaust stream and recycled back to the fuel cell **305** as fuel, the hydrogen from the anode exhaust stream in the second gas stream to the fuel cell **305** reduces the amount of hydrogen required to be produced by the reforming reactor **301**, thereby reducing attendant carbon dioxide by-product production.

In this embodiment of the process of the present invention, carbon dioxide is generated at a rate of no more than 400 grams per kilowatt-hour (400g per kWh) of electricity generated. In a preferred embodiment, carbon dioxide is generated in the process of the present invention at a rate of no more than 350g per kWh, and in a more preferred embodiment, carbon dioxide is generated in the process of the present invention at a rate of no more than 300g per kWh.

In another embodiment, the process of the present invention utilizes a system including a thermally integrated steam reformer, a hydrogen-separating device located exterior to the steam reformer, and a solid oxide fuel cell. Referring now to Fig. 3, the system for practicing the process of this embodiment is similar to that shown in Fig. 1 or in Fig. 2, except that the high temperature hydrogen-separation device **503** is not located in a reforming reactor **501**, but is operatively coupled to the reforming reactor **501** so that a reformed product gas containing hydrogen and carbon oxides formed in the reforming reactor **501** and unreacted hydrocarbons and steam are passed through line **505** to the high temperature hydrogen-separation device **503**. The high temperature hydrogen-separation device **503** is preferably a tubular hydrogen permeable membrane apparatus as described above.

A first gas stream containing hydrogen may be separated from the reformed product gas and unreacted steam and hydrocarbons by the hydrogen separation device **503**. A steam sweep gas may be injected into the hydrogen separation device **503** through line **507** to facilitate separation of the first gas stream. The first gas stream may be fed from the hydrogen separation device to a heat exchanger, and subsequently to a condenser, and then to the solid oxide fuel cell as described above.

Gaseous non-hydrogen reformed products and unreacted feed may be separated as a gaseous stream from the hydrogen separation device **503** via line **509**. The non-hydrogen reformed products and unreacted feed may include carbon dioxide, water (as steam), and small amounts of carbon monoxide and unreacted hydrocarbons.

The non-hydrogen gaseous stream separated from the hydrogen separation device **503** may be a high pressure carbon dioxide gas stream containing at least 0.9, or at least 0.95, or at least 0.98 mole fraction carbon dioxide on a dry basis, and having a pressure of at least 1 MPa, or at least 2 MPa, or at least 2.5 MPa. The high pressure carbon dioxide stream may be treated as described above with respect to the high pressure carbon dioxide stream separated from the reforming reactor with the hydrogen separation membrane located therein.

The remainder of the process utilizing the hydrogen separation device **503** located outside of the reforming reactor **501** may be practiced in the same manner as the process described above with respect to the solid oxide fuel cell and the reforming reactor containing the hydrogen separation membrane therein, with or without a pre-reforming reactor.

Referring now to Fig. 4, a system **600** in accordance with the present invention is shown. The system **600** includes a solid oxide fuel cell **601**, a reforming reactor **603**, a hydrogen separation apparatus **605**, and an anode exhaust conduit **607** and/or a cathode exhaust conduit **637**. The solid oxide fuel cell **601** comprises an anode **609** having an anode inlet **611** adapted to receive a hydrogen containing fuel gas and an anode exhaust outlet **613**, a cathode **615** having a cathode inlet **617** adapted to receive an oxygen containing gas and a cathode exhaust outlet **619**, and an electrolyte **621**, where the electrolyte **621** is positioned between contacting and separating the anode **609** and the cathode **615**. Solid oxide fuel cells useful in the system of the present invention, their anodes, cathodes, and electrolytes are described above.

The system **600** also includes a reforming reactor **603** that provides hydrogen fuel to the anode **609** of the fuel cell **601**. The reforming reactor **603** includes a reforming region **623** that is adapted to reform a vaporized mixture of steam and a feed comprising one or more gaseous hydrocarbons to produce a reformed product gas containing hydrogen. The reforming region **623** may include a reforming catalyst bed **625** with a reforming catalyst **627** therein, where the reforming catalyst **627** may be positioned in the reforming catalyst bed **625** to contact a vaporized mixture of steam and feed in the reforming region **623** to assist in reforming the vaporized mixture of steam and feed in the reforming region **623** to produce the reformed product gas. Reforming catalysts **627** that may be used in the reforming catalyst bed **625** are described above. The reforming reactor **603** includes one or more reforming region inlets **629** coupled in gaseous communication with the reforming region **623** through which steam, a feed comprising one or more gaseous hydrocarbons, or a mixture of steam and a feed comprising one or more gaseous hydrocarbons may be introduced into the reforming region **623**.

The system **600** further includes a hydrogen separation apparatus **605** for separating hydrogen produced in the reforming reactor **603**, where the hydrogen separated by the hydrogen separation apparatus **605** is provided to the anode **609** of the fuel cell **601**. The hydrogen separation apparatus **605** includes a member **631** that is selectively permeable to hydrogen, and a hydrogen gas outlet **633**. In an embodiment, the member **631** that is selectively permeable to hydrogen is located in the reforming region **623** of the reforming reactor **603** in gaseous communication with the reforming region **623** so that hydrogen produced by reforming and/or water gas shift reactions in the reforming region **623** and/or present in the reforming region **623** may be separated from other gaseous compounds in the reforming region **623** through the member **631**. In a preferred embodiment, the hydrogen separation apparatus **605** is a high-temperature hydrogen separation membrane, as described above, where the member **631** is the hydrogen-selective, hydrogen-permeable wall of the membrane.

The hydrogen gas outlet **633** of the hydrogen separation apparatus **605** is located in gaseous communication with the hydrogen permeable member **631** of the hydrogen separation apparatus **605**, preferably through a hydrogen conduit **635**. The hydrogen permeable member **631** is interposed between the reforming region **623** of the reforming reactor **603** and the hydrogen gas outlet **633** and the hydrogen conduit **635** to permit selective flow of hydrogen from the reforming region **623** through the hydrogen permeable member **631** to hydrogen conduit **635** and out of the hydrogen separation apparatus **605** and the reforming reactor **603** through the hydrogen gas outlet **633**.

The hydrogen gas outlet **633** is operatively coupled in gaseous communication with an anode inlet **611** of the anode **609**—through which hydrogen fuel may be fed to the anode **609**—so that hydrogen produced in the reforming reactor **603** and separated therefrom by the hydrogen separation apparatus **605** may be fed to the anode **609** of the fuel cell **601**. In an embodiment, one or more heat exchangers (not shown) may be coupled in gaseous communication between the hydrogen gas outlet **633** and the anode inlet **611** to cool the hydrogen gas stream exiting the hydrogen gas outlet **633** prior to the hydrogen gas stream entering the anode **609** of the fuel cell **601**.

The system **600** may also include at least one anode exhaust conduit **607**. At least a portion of each anode exhaust conduit **607** is located in the reforming region **623** of the reforming reactor **603** positioned within the reforming region **623** in thermal communication with the reforming region **623**. Each anode exhaust conduit **607** is operatively coupled in gaseous communication with an anode exhaust outlet **613** of the anode **609** of the fuel cell **601** so that a hot gas exiting the anode **609** of the fuel cell **601** through the anode exhaust outlet **613** may be communicated to the anode exhaust conduit **607** in the reforming region **623** of the reforming reactor **603** to exchange heat with the catalyst **627** in the reforming region **623** and any steam or feed present in the reforming region **623**.

The system **600** may also include at least one cathode exhaust conduit **637**. At least a portion of each cathode exhaust conduit **637** is located in the reforming region **623** of the reforming reactor **603** positioned within the reforming region **623** in thermal communication with the reforming region **623**. Each cathode exhaust conduit **637** is operatively coupled in gaseous communication with a cathode exhaust outlet **619** of the cathode **615** of the fuel cell **601** so that a hot gas exiting the cathode **615** of the fuel cell **601** through the cathode exhaust outlet **619** may be communicated to the cathode exhaust conduit **637** in the reforming region **623** of the reforming reactor **603** to exchange heat with the catalyst **627** in the reforming region **623** and any steam or feed present in the reforming region **623**.

The system **600** of the present invention includes either at least one anode exhaust conduit **609** as described above, or at least one cathode exhaust conduit **637** as described above, or both, located at least partially in the reforming region **623** of the reforming reactor **603** so that heat from the fuel cell **601** may be provided to the reforming region **623** of the reforming reactor **603** by passing an anode exhaust stream and/or a cathode exhaust stream from the fuel cell **601** through the anode exhaust conduit **609** and/or the cathode exhaust conduit **637**, respectively.

In a preferred embodiment of the system **600**, the anode exhaust conduit **607** may be operatively connected in gaseous communication with the anode inlet **611** of the anode **609** so that hydrogen in the anode exhaust may be recycled back into the anode **609** of the fuel cell **601**. The anode exhaust conduit **607** may have an outlet **639** operatively coupled in gaseous communication with an anode inlet **611** through which an anode exhaust stream may exit the anode exhaust conduit **607** to be fed to the anode inlet **611**.

The system **600** may include one or more heat exchanger(s) **641** to further cool the anode exhaust exiting the anode exhaust conduit **607** prior to feeding the anode exhaust back to the anode **609** through the anode inlet **611**. The heat exchanger(s) **641** may cool the anode exhaust with any cooling medium, however, as described above, preferably the anode exhaust is cooled by exchanging heat with a feed or a feed precursor and/or steam that is to be used in the reforming reactor **603** to produce hydrogen to be fed to the fuel cell **601**.

If the system **600** includes one or more heat exchangers **641**, the heat exchanger(s) **641** are operatively coupled in the system **600** between the anode exhaust conduit **607** and the anode inlet **611** to cool the anode exhaust stream as the anode exhaust stream flows from the anode exhaust conduit **607** to the anode inlet **611**. An inlet **643** of the heat exchanger **641** may be operatively connected in gaseous communication with the anode exhaust conduit outlet **639**, and the outlet **645** of the heat exchanger **641** may be operatively connected in gaseous communication with the anode inlet **611**. If one or more heat exchanger **641** is present in the system **600**, the heat exchangers **641** may be arranged in series, where the heat exchanger inlet **643** of the first heat exchanger **641** is operatively connected in gaseous communication with the anode exhaust conduit outlet **639** and the heat exchanger outlet **645** of the last of the heat exchangers **641** is operatively connected in gaseous communication with the anode inlet **611** of the anode **609** of the fuel cell **601**, where the heat exchanger outlet **645** of each of the serially connected heat exchangers **641**, except the final heat exchanger **641** of the series, may be connected in gaseous communication with the heat exchanger inlet **643** of the next heat exchanger **641** in the series.

In an embodiment, a condenser **647** may be operatively connected in gaseous communication between the heat exchanger outlet **645** or the anode exhaust conduit outlet **639** and the anode inlet **611** of the anode **609** of the fuel cell **601** to separate hydrogen from water/steam in the anode exhaust exiting the heat exchanger(s) **641** or the anode exhaust conduit **609** prior to feeding the hydrogen to the anode inlet **611**. As noted above, when hydrogen is supplied as fuel to the fuel cell **601** the anode exhaust contains unreacted hydrogen and water produced by oxidation of hydrogen in the fuel cell **601**. The cooled anode exhaust stream exiting the heat exchanger(s) **641** or the anode exhaust conduit **609** may be cooled in the condenser **647** sufficiently to condense and remove water from the cooled anode exhaust stream and thereby provide a high hydrogen content gas stream to the anode **609** of the fuel cell **601**.

Optionally, the system **600** may include a pre-reforming reactor **649** for converting a feed precursor, such as those described above, to a feed useful in the reforming reactor **603**. The pre-reforming reactor **649** may include a pre-reforming region **651** that is adapted to receive a liquid or vaporized mixture of steam and a feed precursor comprising one or more hydrocarbons to produce a feed to be provided to the reforming reactor **603**. The pre-reforming reactor **649** may include a pre-reforming catalyst bed **653** with a pre-reforming catalyst **655** located therein positioned to contact a vapor in the pre-reforming region **651** of the pre-reforming reactor **649**. Pre-reforming catalysts that may be used in the pre-reforming catalyst bed **653** are described above. The pre-reforming reactor **649** may include one or more pre-reforming stream inlets **657** coupled in gas/fluid communication with the pre-reforming region **651** and adapted to receive a feed precursor comprising one or more hydrocarbons, steam, or a mixture thereof and communicate the steam, feed precursor, or mixture thereof to the pre-reforming region **651**. The pre-reforming reactor **649** may include an outlet **659** operatively coupled in gaseous communication with the reforming region inlet **629** of the reforming reactor **603** to supply feed formed in the pre-reforming reactor **649** to the reforming reactor **603**. In one embodiment, a compressor **661** may be included in the system **600**, where the compressor **661** is operatively connected in gaseous communication between the pre-reforming reactor outlet **659** and the reforming region inlet **625** so the compressor **661** may compress a feed produced by the pre-reforming reactor **649** prior to the feed being fed to the reforming reactor **603**.

The system **600** including a pre-reforming reactor **649** may also include at least one pre-reformer anode exhaust conduit **663**. At least a portion of each pre-reformer anode exhaust conduit **663** is located in the pre-reforming region **651** of the pre-reforming reactor **649** positioned within the pre-reforming region **651** in thermal communication with the pre-reforming region **651**. Each pre-reformer anode exhaust conduit **665** may be operatively coupled in gaseous communication with an anode exhaust outlet **613** of the anode **609** of the fuel cell **601** so that a hot gas exiting the anode **609** of the fuel cell **601** through an anode exhaust outlet **613** may be communicated to the pre-reformer anode exhaust conduit **665** in the pre-reforming region **651** of the pre-reforming reactor **649** to exchange heat with the pre-reforming catalyst **655** in the pre-reforming region **651** and any steam or feed precursor present in the pre-reforming region **651**.

The system **600** including a pre-reforming reactor **649** may also include at least one pre-reformer cathode exhaust conduit **665**. At least a portion of each pre-reformer cathode exhaust conduit **665** is located in the pre-reforming region **651** of the pre-reforming reactor **649** positioned within the pre-reforming region **651** in thermal communication with the pre-reforming region **651**. Each pre-reformer cathode exhaust conduit **665** is operatively coupled in gaseous communication with a cathode exhaust outlet **619** of the cathode **615** of the fuel cell **601** so that a hot gas exiting the cathode **615** of the fuel cell **601** through a cathode exhaust outlet **619** may be communicated to the pre-reformer cathode exhaust conduit **665** in the pre-reforming region **651** of the pre-reforming reactor **649** to exchange heat with the pre-reformer catalyst **655** in the pre-reforming region **651** and any steam or feed precursor present in the pre-reforming region **651**.

In a system **600** including a pre-reforming reactor **649** and at least one pre-reformer anode exhaust conduit **663** and at least one anode exhaust conduit **607**, the outlet **667** of the pre-reformer anode exhaust conduit **663** may be operatively connected to the anode exhaust conduit **607** so that an anode exhaust stream may be fed from the pre-reformer anode exhaust conduit **663** to the anode exhaust conduit **607**. In a system **600** including a pre-reforming reactor **649** and at least one pre-reformer cathode exhaust conduit **665** and at least one cathode exhaust conduit **637**, the outlet **669** of the pre-reformer cathode exhaust conduit **665** may be operatively connected to the cathode exhaust conduit **637** so that a cathode exhaust stream may be fed from the pre-reformer cathode exhaust conduit **665** to the cathode exhaust conduit **637**.

In another embodiment, as shown in Fig. 5, the hydrogen separation apparatus **705** may be located outside the reforming reactor **703**. The hydrogen-permeable, hydrogen-selective member **731** may be operatively coupled in gaseous communication with the reforming region **723** of the reforming reactor **703** so the reformed gas products produced in the reforming region **723** may pass from the reforming region **723** to the member **731** so hydrogen may be separated from the reformed product gas by the member **731**. In one embodiment, the member **731** may be a high-temperature hydrogen-permeable, hydrogen-selective membrane, as described above. In another embodiment, the member **731** may be a pressure swing adsorber. In an embodiment, particularly if the member **731** is a pressure swing adsorber, one or more heat exchangers (not shown) may be coupled in gaseous communication between the reforming region **723** of the reforming reactor **703** and the member **731** to cool the reformed product gas prior to separating hydrogen from the reformed product gas with the member **731**.

The hydrogen gas outlet **733** of the hydrogen separation apparatus **705** is located in gaseous communication with the selectively hydrogen permeable member **731** of the hydrogen separation apparatus **705**, preferably through a hydrogen conduit **735**. The selectively hydrogen permeable member **731** is interposed between the reforming region **723** of the reforming reactor **703** and the hydrogen gas outlet **733** (and the hydrogen conduit **735)** to permit selective flow of hydrogen from the reforming region **723** through the hydrogen permeable member **731** to hydrogen conduit **735** and out of the hydrogen separation apparatus **705** through hydrogen gas outlet **733**.

The hydrogen gas outlet **733** is operatively coupled in gaseous communication with the anode inlet **711** of the fuel cell **701** so that hydrogen produced in the reforming reactor **703** and separated from a reformed product gas by the hydrogen separation apparatus **705** may be fed to the anode **709** of the fuel cell **701**. In an embodiment, one or more heat exchangers (not shown) may be coupled in gaseous communication between the hydrogen gas outlet **733** and the anode inlet **711** to cool the hydrogen gas stream exiting the hydrogen gas outlet **733** prior to the hydrogen gas stream entering the anode **709** of the fuel cell **701**.

In an embodiment, the system of the present invention may be a system as depicted in Fig. 1 and described above in the description of a process of the present invention.

In an embodiment, the system of the present invention may be a system as depicted in Fig. 2 and described above in the description of a process of the present invention.

CLAIMS

1. A system for generating electricity, comprising:
    - a) a solid oxide fuel cell comprising
        - 1) an anode having
            - (i) an anode inlet; and
            - (ii) an anode exhaust outlet
        - 2) a cathode having
            - (i) a cathode inlet; and
            - (ii) a cathode exhaust outlet; and
        - 3) an electrolyte positioned between, contacting, and separating the anode and the cathode;
    - b) a reforming reactor comprising
        - 1) a reforming region adapted to reform a vaporized mixture of steam and a feed comprising one or more gaseous hydrocarbons, said reforming region containing a reforming catalyst bed with at least one reforming catalyst therein positioned to contact the vaporized mixture of steam and feed in the reforming region; and
        - 2) one or more reforming region inlets coupled in gaseous communication with the reforming region through which steam, a feed comprising one or more gaseous hydrocarbons, or a vaporized mixture of steam and a feed comprising one or more gaseous hydrocarbons may be introduced to the reforming region;
    - c) a hydrogen separation apparatus having
        - 1) a member selectively permeable to hydrogen located in the reforming region of the reforming reactor and in gaseous communication with the reforming region of the reforming reactor; and
        - 2) a hydrogen gas outlet operatively coupled in gaseous communication with the member, the member being interposed between the reforming region of the reforming reactor and the hydrogen gas outlet to permit selective flow of hydrogen from the reforming region to the hydrogen gas outlet through the member, wherein the hydrogen gas outlet is operatively coupled in gaseous communication with the anode inlet of the fuel cell;

d) an anode exhaust conduit operatively coupled in gaseous communication with the anode exhaust outlet, at least a portion of the anode exhaust conduit being located in the reforming region of the reforming reactor, the anode exhaust conduit being positioned within the reforming region of the reforming reactor in thermal communication with the reforming region effective to exchange heat from a hot gas exiting the anode of the solid oxide fuel cell with the catalyst in the reforming region and any steam and feed present in the reforming region.

2. The system of claim 1 further comprising:

a cathode exhaust conduit operatively coupled in gaseous communication with the cathode exhaust outlet, at least a portion of the cathode exhaust conduit being located within the reforming region of the reforming reactor, the cathode exhaust conduit being positioned within the reforming region of the reforming reactor in thermal communication with the reforming region effective to exchange heat from a hot gas exiting the cathode of the solid oxide fuel cell with the catalyst in the reforming region and any steam and feed present in the reforming region.

3. The system of claim 1 or 2 wherein the member of the hydrogen separation apparatus is a membrane that is selectively permeable to hydrogen.

4. The system of claim 1 or 2 wherein the hydrogen separation apparatus is a pressure swing adsorber.

5. The system of claim 1 or any of claims 2-4 wherein an outlet of the anode exhaust conduit is operatively connected in gaseous communication with the anode inlet.

6. The system of claim 5 further comprising a condenser operatively connected in gaseous communication between the outlet of the anode exhaust conduit and the anode inlet.

7. The system of claim 5 further comprising a heat exchanger and a condenser, where the heat exchanger is operatively coupled in gaseous communication between the anode

exhaust conduit outlet and the condenser and the condenser is operatively coupled in gaseous communication between the heat exchanger and the anode inlet.

8. The system of claim 1 or any of claims 2-7 further comprising a pre-reforming reactor, said pre-reforming reactor comprising a pre-reforming region adapted to receive a liquid or vaporized mixture of steam and a feed precursor comprising one or more hydrocarbons, said pre-reforming region containing a catalyst bed with one or more pre-reforming catalysts therein, said pre-reforming region having a pre-reforming stream inlet coupled in gas/fluid communication with the pre-reforming region and adapted to receive a feed precursor comprising one or more hydrocarbons, steam, or a mixture thereof, and a pre-reforming stream outlet operatively coupled in gaseous communication with the reforming region inlet of the reforming reactor.

9. The system of claim 8 wherein a pre-reformer anode exhaust conduit is operatively coupled in gaseous communication with the anode exhaust outlet, at least a portion of the pre-reformer anode exhaust conduit being located in the pre-reforming region of the pre-reforming reactor, the pre-reformer anode exhaust conduit being positioned within the pre-reforming region of the pre-reforming reactor in thermal communication with the pre-reforming region effective to exchange heat from a hot gas exiting the anode of the solid oxide fuel cell with the catalyst in the pre-reforming region and any steam and feed precursor present in the pre-reforming region.

10. The system of claim 9 wherein the pre-reformer anode exhaust conduit outlet is operatively coupled in gaseous communication with the anode exhaust conduit to provide a hot gas exiting the pre-reformer anode exhaust conduit to the anode exhaust conduit.

11. A system for generating electricity, comprising:
  a) a solid oxide fuel cell comprising
    1) an anode having
      (i) an anode inlet; and
      (ii) an anode exhaust outlet
    2) a cathode having
      (i) a cathode inlet; and

(ii) a cathode exhaust outlet; and

3) an electrolyte positioned between, contacting, and separating the anode and the cathode;

b) a reforming reactor comprising

1) a reforming region adapted to reform a vaporized mixture of steam and a feed comprising one or more gaseous hydrocarbons, said reforming region containing a reforming catalyst bed with at least one reforming catalyst therein positioned to contact the vaporized mixture of steam and feed in the reforming region; and

2) one or more reforming region inlets coupled in gaseous communication with the reforming region through which steam, a feed comprising one or more gaseous hydrocarbons, or a vaporized mixture of steam and a feed comprising one or more gaseous hydrocarbons may be introduced to the reforming region;

c) a hydrogen separation apparatus having

1) a member selectively permeable to hydrogen located in the reforming region of the reforming reactor and in gaseous communication with the reforming region of the reforming reactor; and

2) a hydrogen gas outlet operatively coupled in gaseous communication with the member, the member being interposed between the reforming region of the reforming reactor and the hydrogen gas outlet to permit selective flow of hydrogen from the reforming region to the hydrogen gas outlet through the member, wherein the hydrogen gas outlet is operatively coupled in gaseous communication with the anode inlet of the fuel cell;

d) an cathode exhaust conduit operatively coupled in gaseous communication with the cathode exhaust outlet, at least a portion of the cathode exhaust conduit being located in the reforming region of the reforming reactor, the cathode exhaust conduit being positioned within the reforming region of the reforming reactor in thermal communication with the reforming region effective to exchange heat from a hot gas exiting the cathode of the solid oxide fuel cell with the catalyst in the reforming region and any steam and feed present in the reforming region.

12. The system of claim 11 further comprising a pre-reforming reactor, said pre-reforming reactor comprising a pre-reforming region adapted to receive a liquid or vaporized mixture of steam and a feed precursor comprising one or more hydrocarbons, said pre-reforming region containing a catalyst bed with one or more pre-reforming catalysts therein, said pre-reforming region having a pre-reforming stream inlet operatively coupled in gas/fluid communication with the pre-reforming region and adapted to receive a feed precursor comprising one or more hydrocarbons, steam, or a mixture thereof, and a pre-reforming stream outlet operatively coupled in gaseous communication with the reforming region inlet of the reforming reactor.

13. The system of claim 12 wherein a pre-reformer cathode exhaust conduit is operatively coupled in gaseous communication with the cathode exhaust outlet, at least a portion of the pre-reformer cathode exhaust conduit being located in the pre-reforming region of the pre-reforming reactor, the pre-reformer cathode exhaust conduit being positioned within the pre-reforming region of the pre-reforming reactor in thermal communication with the pre-reforming region effective to exchange heat from a hot gas exiting the cathode of the solid oxide fuel cell with the catalyst in the pre-reforming region and any steam and feed precursor present in the pre-reforming region.

14. The system of claim 13 wherein the pre-reformer cathode exhaust conduit outlet is operatively coupled in gaseous communication with the cathode exhaust conduit to provide a hot gas exiting the pre-reformer cathode exhaust conduit to the cathode exhaust conduit.

15. A system for generating electricity, comprising:
    a) a solid oxide fuel cell comprising
        1) an anode having
            (i) an anode inlet
            (ii) an anode exhaust outlet
        2) a cathode having
            (i) a cathode inlet; and
            (ii) a cathode exhaust outlet; and
        3) an electrolyte positioned between, contacting, and separating the anode and the cathode;

b) a reforming reactor comprising

1) a reforming region adapted to reform a vaporized mixture of steam and a feed comprising one or more gaseous hydrocarbons, said reforming region containing a reforming catalyst bed with at least one reforming catalyst therein positioned to contact the vaporized mixture of steam and feed in the reforming region; and

2) one or more reforming region inlets coupled in gaseous communication with the reforming region through which steam, a feed comprising one or more gaseous hydrocarbons, or a vaporized mixture of steam and a feed comprising one or more gaseous hydrocarbons may be introduced to the reforming region;

c) a hydrogen separation apparatus having

1) a member selectively permeable to hydrogen operatively coupled in gaseous communication with the reforming region of the reforming reactor; and

2) a hydrogen gas outlet operatively coupled in gaseous communication with the member, the member being interposed between the reforming region of the reforming reactor and the hydrogen gas outlet to permit selective flow of hydrogen from the reforming region to the hydrogen gas outlet through the member, wherein the hydrogen gas outlet is operatively coupled in gaseous communication with the anode inlet of the fuel cell;

d) an anode exhaust conduit operatively coupled in gaseous communication with the anode exhaust outlet, at least a portion of the anode exhaust conduit being located in the reforming region of the reforming reactor, the anode exhaust conduit being positioned within the reforming region of the reforming reactor in thermal communication with the reforming region effective to exchange heat from a hot gas exiting the anode of the solid oxide fuel cell with the catalyst in the reforming region and any steam and feed present in the reforming region.

16. The system of claim 15 further comprising:

a cathode exhaust conduit operatively coupled in gaseous communication with the cathode exhaust outlet, at least a portion of the cathode exhaust conduit being located within the reforming region of the reforming reactor, the cathode exhaust conduit being positioned within the reforming region of the reforming reactor in thermal communication with the reforming region effective to exchange heat from a hot gas exiting the cathode of the solid oxide fuel cell with the catalyst in the reforming region and any steam and feed present in the reforming region.

17. The system of claim 15 or claim 16 further comprising a pre-reforming reactor, said pre-reforming reactor comprising a pre-reforming region adapted to receive a liquid or vaporized mixture of steam and a feed precursor comprising one or more hydrocarbons, said pre-reforming region containing a catalyst bed with one or more pre-reforming catalysts therein, said pre-reforming region having a pre-reforming stream inlet operatively coupled in gas/fluid communication with the pre-reforming region and adapted to receive a feed precursor comprising one or more hydrocarbons, steam, or a mixture thereof, and a pre-reforming stream outlet operatively coupled in gaseous communication with the reforming region inlet of the reforming reactor.

18. The system of claim 17 wherein a pre-reformer anode exhaust conduit is operatively coupled in gaseous communication with the anode exhaust outlet, at least a portion of the pre-reformer anode exhaust conduit being located in the pre-reforming region of the pre-reforming reactor, the pre-reformer anode exhaust conduit being positioned within the pre-reforming region of the pre-reforming reactor in thermal communication with the pre-reforming region effective to exchange heat from a hot gas exiting the anode of the solid oxide fuel cell with the catalyst in the pre-reforming region and any steam and feed precursor present in the pre-reforming region.

19. The system of claim 15 or any of claims 16-18 wherein an outlet of the anode exhaust conduit is operatively connected in gaseous communication with the anode inlet.

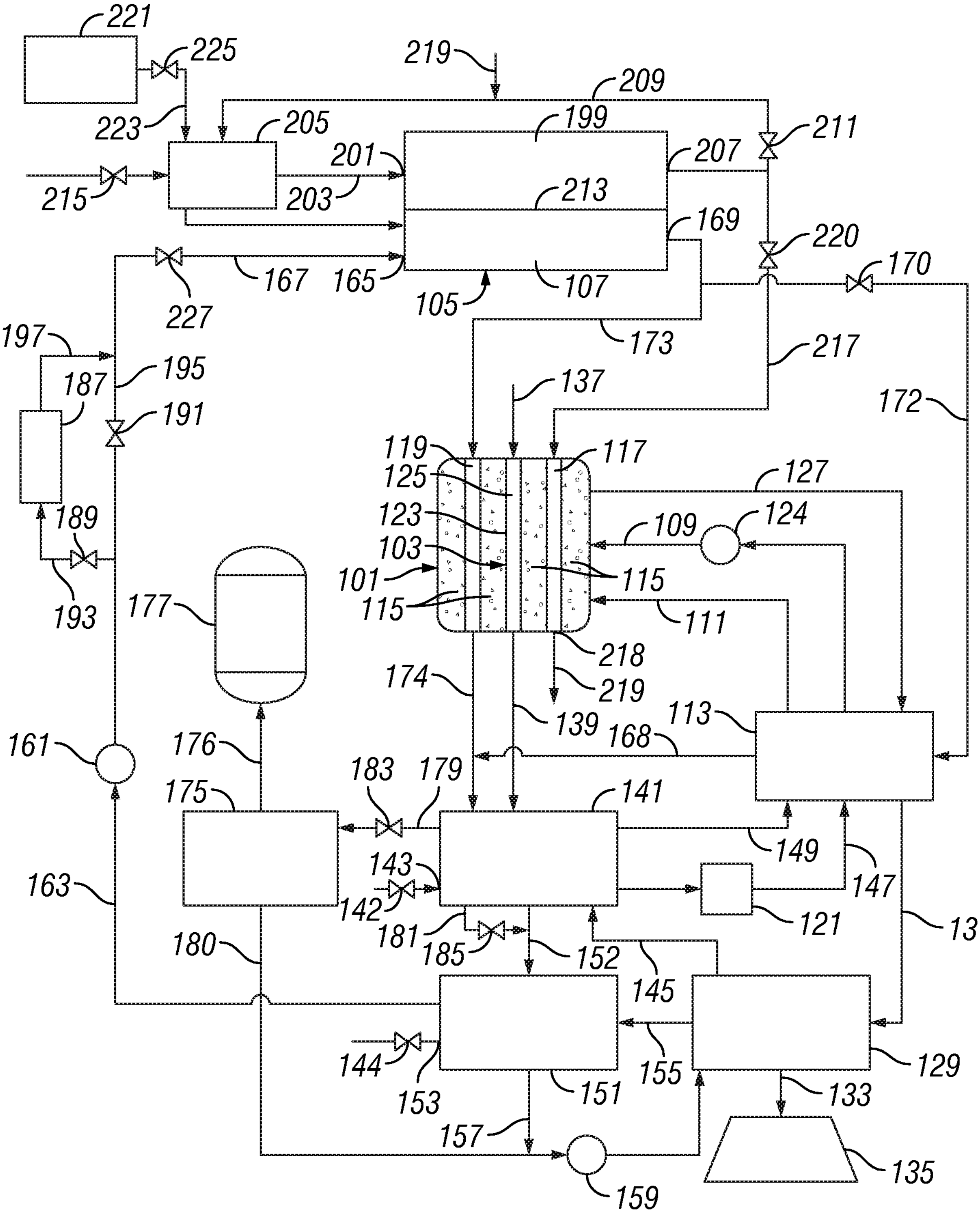
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FIG. 1

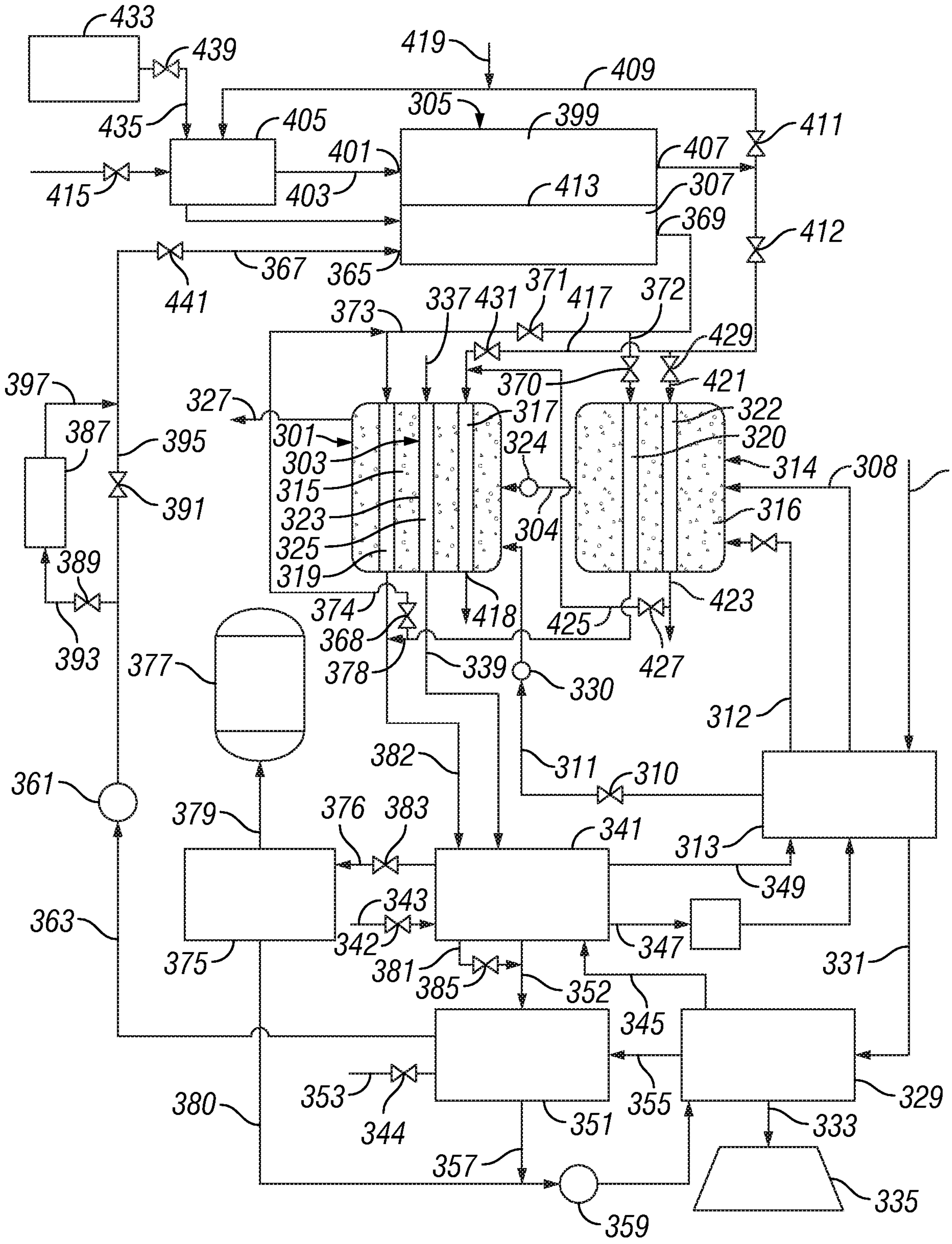
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FIG. 2

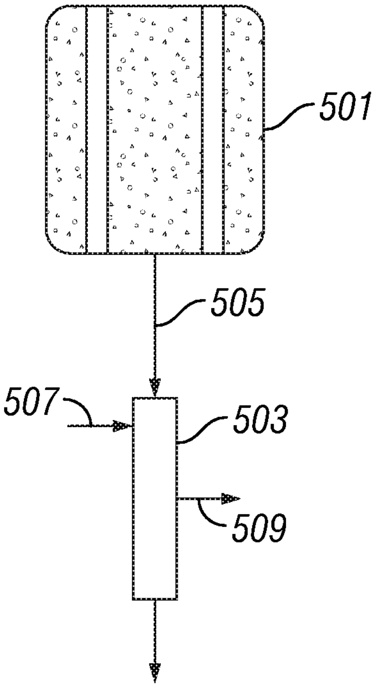

FIG. 3

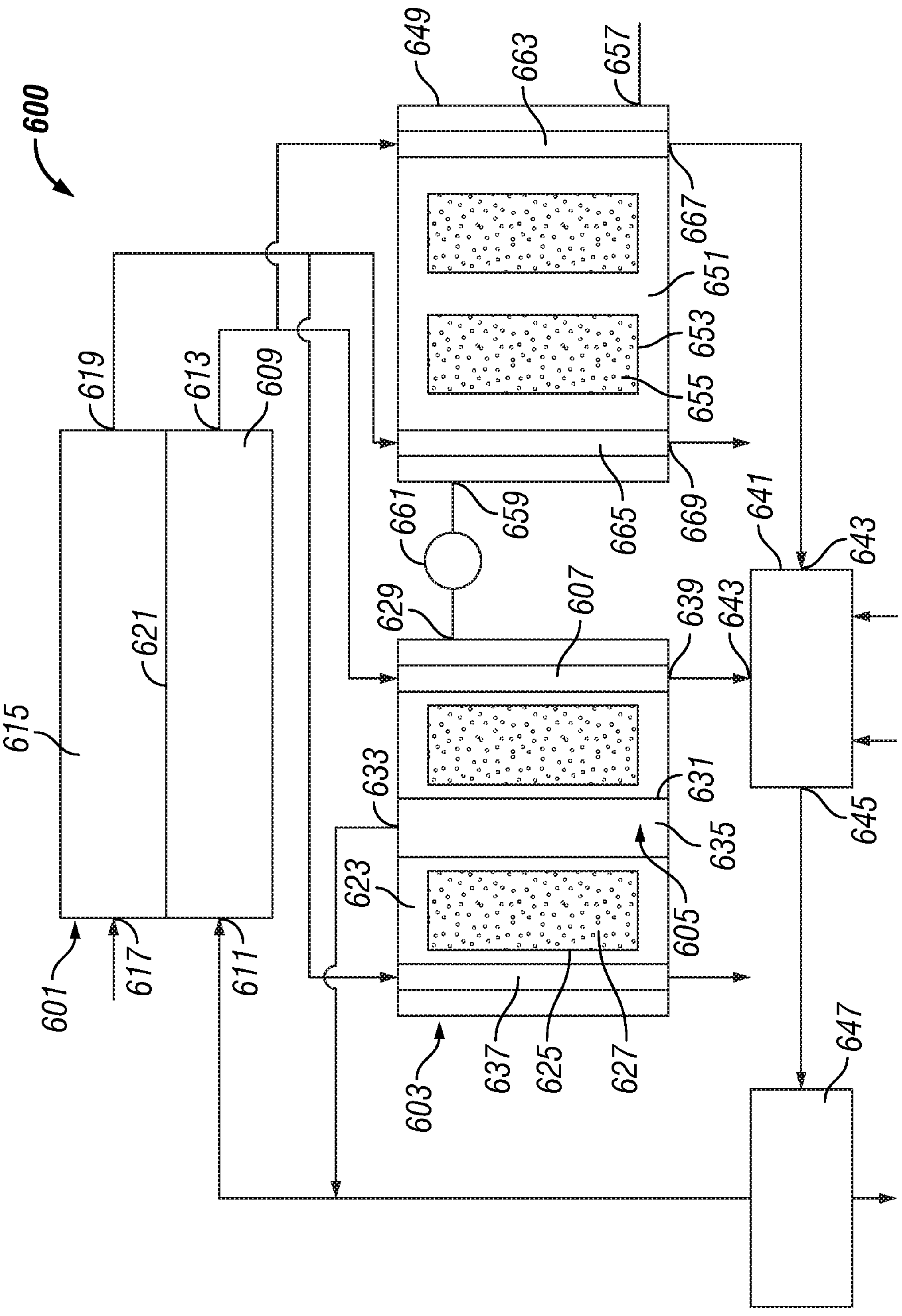
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FIG. 4

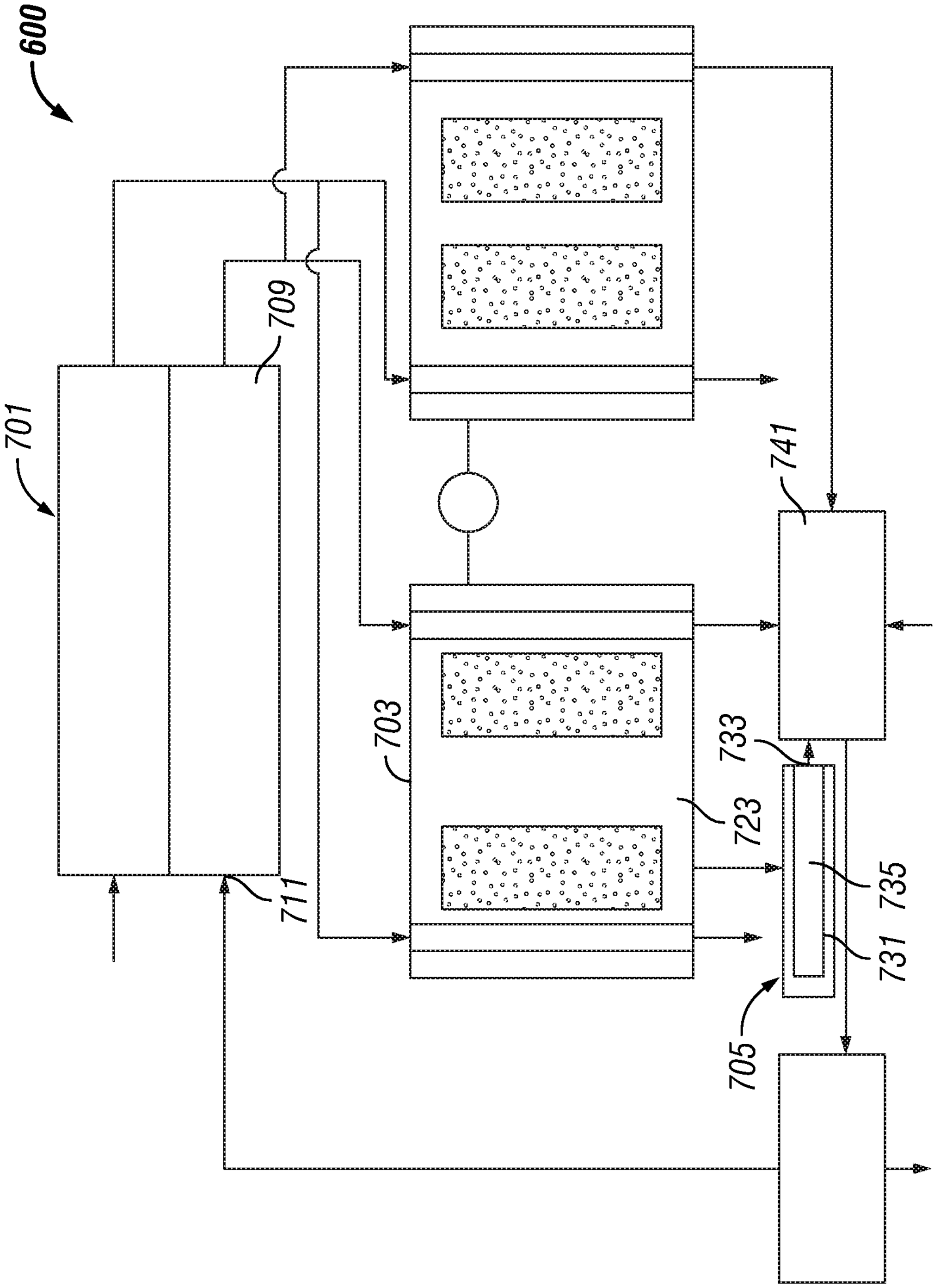

FIG. 5

INTERNATIONAL SEARCH REPORT

International application No
PCT/US2008/086777

A. CLASSIFICATION OF SUBJECT MATTER
INV. H01M8/06

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
H01M

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	WO 2004/025767 A (PROTOTECH AS [NO]; VIK ARILD [NO]; RAEHEIM ARNE [NO]; SAMUELS ADRIAN J) 25 March 2004 (2004-03-25) page 8, lines 12-37 page 10, lines 4-7 page 16, lines 2-13 page 17, lines 3-12 page 23, line 14	1-19
X	WO 2007/117406 A (BLOOM ENERGY CORP [US]; AARON STUART [US]; BALLANTINE ARNE WATSON [US]) 18 October 2007 (2007-10-18) paragraphs [0064] - [0066]; figure 9 paragraphs [0068] - [0073]; figure 10	1-19

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☒ Further documents are listed in the continuation of Box C.

☒ See patent family annex.

* Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

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Date of the actual completion of the international search 11 March 2009	Date of mailing of the international search report 19/03/2009
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