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(54) Title: INTEGRATED POWER GENERATION AND CHEMICAL PRODUCTION USING SOLID OXIDE FUEL CELLS

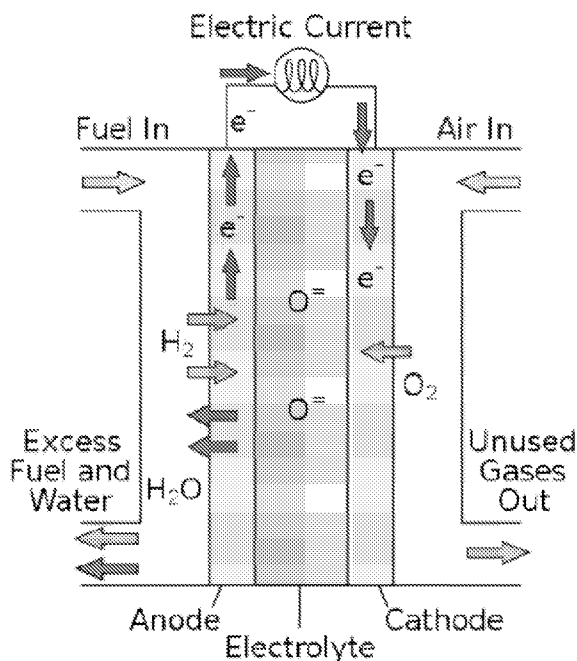


FIG. 3

(57) Abstract: In various aspects, systems and methods are provided for operating a solid oxide fuel cell at conditions that can improve or optimize the combined electrical efficiency and chemical efficiency of the fuel cell. Instead of selecting conventional conditions for maximizing the electrical efficiency of a fuel cell, the operating conditions can allow for output of excess synthesis gas and/or hydrogen in the anode exhaust of the fuel cell. The synthesis gas and/or hydrogen can then be used in a variety of applications, including chemical synthesis processes and collection of hydrogen for use as a fuel.



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INTEGRATED POWER GENERATION AND CHEMICAL PRODUCTION
USING SOLID OXIDE FUEL CELLS

FIELD OF THE INVENTION

[0001] In various aspects, the invention is related to chemical production and/or power generation processes integrated with electrical power production using solid oxide fuel cells.

BACKGROUND OF THE INVENTION

[0002] Solid oxide fuel cells utilize hydrogen and/or other fuels to generate electricity. The hydrogen may be provided by reforming methane or other reformable fuels in a steam reformer that is upstream of the fuel cell or within the fuel cell. Reformable fuels can encompass hydrocarbonaceous materials that can be reacted with steam and/or oxygen at elevated temperature and/or pressure to produce a gaseous product that comprises hydrogen. Alternatively or additionally, fuel can be reformed in the anode cell in a solid oxide fuel cell, which can be operated to create conditions that are suitable for reforming fuels in the anode. Alternately or additionally, the reforming can occur both externally and internally to the fuel cell.

[0003] Traditionally, solid oxide fuel cells are operated to maximize electricity production per unit of fuel input, which may be referred to as the fuel cell's electrical efficiency. This maximization can be based on the fuel cell alone or in a combined heat and power application. In order to achieve increased electrical production and to manage the heat generation, fuel utilization within a fuel cell is typically maintained at 70% to 85%.

[0004] U.S. Patent Application Publication No. 2005/0123810 describes a system and method for co-production of hydrogen and electrical energy. The co-production system comprises a fuel cell and a separation unit, which is configured to receive the anode exhaust stream and separate hydrogen. A portion of the anode exhaust is also recycled to the anode inlet. The operating ranges given in the '810 publication appear to be based on a molten carbonate fuel cell. Solid oxide fuel cells are described as an alternative.

SUMMARY OF THE INVENTION

[0005] In an aspect, a method for producing electricity and hydrogen or syngas using a solid oxide fuel cell having an anode and cathode is provided. The method introducing a fuel stream comprising a reformable fuel into the anode of the solid oxide fuel cell, an internal reforming element associated with the anode of the solid oxide fuel cell, or a combination thereof; introducing a cathode inlet stream comprising O₂ into the cathode of the solid oxide fuel cell; generating electricity within the solid oxide fuel cell; and withdrawing, from an anode exhaust, a gas stream comprising H₂, a gas stream comprising H₂ and CO, or a combination thereof, wherein an electrical efficiency for the solid oxide fuel cell is between about 10% and about 50% and a total fuel cell productivity for the solid oxide fuel cell is at least about 150 mW/cm².

BRIEF DESCRIPTION OF THE FIGURES

[0006] FIG. 1 schematically shows an example of a configuration for solid oxide fuel cells and associated reforming and separation stages.

[0007] FIG. 2 schematically shows another example of a configuration for solid oxide fuel cells and associated reforming and separation stages.

[0008] FIG. 3 schematically shows an example of the operation of a solid oxide fuel cell.

DETAILED DESCRIPTION OF THE EMBODIMENTS

Overview

[0009] In various aspects, systems and methods are provided that provide for the production of large amounts of hydrogen or synthesis gas, in addition to the production of electricity, from a solid oxide fuel cell (SOFC) at high total fuel cell efficiency. Aspects of the present invention can use either planar cells or tubular cells. The total fuel cell efficiency refers generally to the combined electrical efficiency and chemical efficiency of the fuel cell. A fuller definition of total fuel cell efficiency is provided subsequently.

[0010] Typical fuel cell systems can be designed and operated for optimized electrical efficiency at the expense of any other parameter(s). Heat produced, whether in-situ and/or as the result of combusting off-gases and anode products, can be employed to an extent needed to maintain fuel cell operations at steady conditions. As with most electricity generation methods, conventional fuel cell systems primarily

value the electrical product. Conventional fuel cell systems can be used in applications where the primary purpose is the production of efficient electrical power, such as in distributed generation or backup generation.

[0011] Aspects of the present invention can establish fuel cell operating parameters to cause the total fuel cell efficiency to exceed conventional fuel cell efficiency.

Additionally, or alternately, the present invention provides a method to increase the total fuel cell productivity while maintaining very high overall system efficiency. In one aspect, productivity is the total amount of useful products (*e.g.*, syngas, heat, electricity) produced per unit of time for a designated amount of fuel cell capacity, for example as measured by the cross sectional area of a fuel cell. Instead of selecting conventional conditions for maximizing the electrical efficiency of a fuel cell, operating conditions can produce much higher total fuel cell efficiency and/or productivity for the overall system if the electrical efficiency is allowed to fall below the optimal electrical efficiency sought in the typical fuel cell systems described above. As described in more detail below, total fuel cell efficiency is a measure of the amount of energy generated by a fuel cell relative to the amount of energy delivered to the fuel cell, while productivity is a measure of the amount of energy generated (the total chemical, electrical and heat energy) by a fuel cell relative to the size (such as anode area) of the fuel cell. The conditions that can achieve high total fuel cell efficiency and/or productivity can allow for output of excess synthesis gas and/or hydrogen in the anode exhaust of the fuel cell and can be achieved by completely or partially decoupling the inputs and outputs from the anode and cathode so as to allow excess production of some products. This excess can be enabled, for example, by decreasing the electrical efficiency of the cell (*e.g.*, by operating at lower voltage) and/or using the heat generated in-situ for efficient production of chemical energy (*e.g.*, in the form of syngas). As a result, the fuel cell can process a much larger amount of total fuel input into the anode while maintaining a total output efficiency (the sum of chemical, electrical, and useful thermal energy) that is similar to or higher than what is known in the art. The higher productivity allows for more efficient use of the fuel cell within the combined system.

[0012] The electrochemical processes occurring in the anode may result in an anode output flow of syngas containing at least a combination of H₂, CO, and CO₂. A water-

gas shift reaction can then be used to generate a desired composition of synthesis gas and/or to increase or maximize H_2 production relative to other syngas components. The synthesis gas and/or hydrogen can then be used in a variety of applications, including but not limited to chemical synthesis processes and/or collection of hydrogen for use as a “clean” fuel.

[0013] As used herein, the term “electrical efficiency” (“EE”) is defined as the electrochemical power produced by the fuel cell divided by the rate of Lower Heating Value (“LHV”) of fuel input to the fuel cell. The fuel inputs to the fuel cell includes both fuel delivered to the anode as well as any fuel used to maintain the temperature of the fuel cell, such as fuel delivered to a burner associated with a fuel cell. In this description, the power produced by the fuel may be described in terms of LHV(el) fuel rate.

[0014] As used herein, the term “electrochemical power” or LHV(el) is the power generated by the circuit connecting the cathode to the anode in the fuel cell and the transfer of oxygen ions across the fuel cell’s electrolyte. Electrochemical power excludes power produced or consumed by equipment upstream or downstream from the fuel cell. For example, electricity produced from heat in a fuel cell exhaust stream is not considered part of the electrochemical power. Similarly, power generated by a gas turbine or other equipment upstream of the fuel cell is not part of the electrochemical power generated. The “electrochemical power” does not take electrical power consumed during operation of the fuel cell into account, or any loss incurred by conversion of the direct current to alternating current. In other words, electrical power used to supply the fuel cell operation or otherwise operate the fuel cell is not subtracted from the direct current power produced by the fuel cell. As used herein, the power density is the current density multiplied by voltage. As used herein, the current density is the current per unit area. As used herein, the total fuel cell power is the power density multiplied by the fuel cell area.

[0015] As used herein, the term “anode fuel input,” designated as LHV(anode_in), is the amount of fuel within the anode inlet stream. The term “fuel input”, designated as LHV(in), is the total amount of fuel delivered to the fuel cell, including both the amount of fuel within the anode inlet stream and the amount of fuel used to maintain the temperature of the fuel cell. The fuel may include both reformable and

nonreformable fuels, based on the definition of a reformable fuel provided herein. Fuel input is not the same as fuel utilization.

[0016] As used herein, the term “total fuel cell efficiency” (“TFCE”) is defined as: the electrochemical power generated by the fuel cell, plus the rate of LHV of syngas produced by the fuel cell, divided by the rate of LHV of fuel input to the anode. In other words, $TFCE = (LHV(el) + LHV(sg\ net))/LHV(anode_in)$, where $LHV(anode_in)$ refers to rate at which the LHV of the fuel components (such as H_2 , CH_4 , and/or CO) delivered to the anode and $LHV(sg\ net)$ refers to a rate at which syngas (H_2 , CO) is produced in the anode, which is the difference between syngas input to the anode and syngas output from the anode. $LHV(el)$ describes the electrochemical power generation of the fuel cell. The total fuel cell efficiency excludes heat generated by the fuel cell that is put to beneficial use outside of the fuel cell. In operation, heat generated by the fuel cell may be put to beneficial use by downstream equipment. For example, the heat may be used to generate additional electricity or to heat water. These uses, which occur apart from the fuel cell, are not part of the total fuel cell efficiency, as the term is used in this application. The total fuel cell efficiency is for the fuel cell operation only, and does not include power production, or consumption, upstream, or downstream, of the fuel cell.

[0017] As used herein, the term “chemical efficiency” is defined as the lower heating value of H_2 and CO in the anode exhaust of the fuel cell, or $LHV(sg\ out)$, divided by the fuel input, or $LHV(in)$.

[0018] As used herein, the term “total fuel cell productivity” (“TFCP”) is defined as the total energy value of products produced per unit of cross-section fuel-cell area per unit of time due to the transformation of the input fuel. The fuel may be transformed in the oxidation reaction, the reformation reaction, and/or the water gas shift reaction. The total energy of the products may be expressed in any convenient units, such as $mW\ per\ cm^2$. The products produced by the fuel cell can include electrochemical power, synthesis gas and/or hydrogen, and heat. The heat produced may be determined by measuring the temperature difference between the anode inlet and the anode outlet. As an example, the productivity of a fuel cell could be expressed as $mW\ per\ cm^2$ of cross sectional area of the fuel cell anode. Fuel cell operating conditions can optionally be

selected to produce both a high total fuel cell productivity and a high total fuel cell efficiency.

[0019] As used herein, the term “total reformable fuel productivity” (“TRFP”) is the difference between the LHV of the reformable fuel input to the anode and the LHV of the reformable fuel received from the anode outlet per unit² of the fuel cell’s cross sectional area. The difference between the reformable fuel in the anode inlet and outlet can be about equal to the amount of the reformable fuel converted into synthesis gas and/or hydrogen minus the amount of newly produced synthesis gas and/or hydrogen that is consumed in the oxidation reaction that ultimately produces electricity. Newly produced synthesis gas and/or hydrogen are produced in the anode or in associated reforming stages heat integrated with the fuel cell. Synthesis gas and/or hydrogen that are provided to the anode inlet are not newly produced. Fuel cell operating conditions can optionally be selected to produce both a high total reformable fuel productivity and a high total fuel cell efficiency.

[0020] In some aspects, the operation of the fuel cells can be characterized based on electrical efficiency. Where fuel cells are operated to have a low electrical efficiency (EE), a solid oxide fuel cell can be operated to have an electrical efficiency of about 50% or less, for example, about 45% EE or less, about 40% EE or less, about 35% EE or less, or about 30% EE or less, about 25% EE or less, about 20% EE or less, about 15% EE or less, or about 10% EE or less. Additionally or alternately, the EE can be at least about 5%, or at least about 10%, or at least about 15%, at least about 20%, at least about 25%, or at least about 30%. Further additionally or alternately, the operation of the fuel cells can be characterized based on total fuel cell efficiency (TFCE), such as a combined electrical efficiency and chemical efficiency of the fuel cell(s). Where fuel cells are operated to have a high total fuel cell efficiency, a solid oxide fuel cell can be operated to have a TFCE (and/or combined electrical efficiency and chemical efficiency) of about 55% or more, for example, about 60% or more, or about 65% or more, or about 70% or more, or about 75% or more, or about 80% or more, or about 85% or more. It is noted that, for a total fuel cell efficiency and/or combined electrical efficiency and chemical efficiency, any additional electricity generated from use of excess heat generated by the fuel cell can be excluded from the efficiency calculation.

[0021] In various aspects of the invention, the operation of the fuel cells can be characterized based on a desired electrical efficiency of about 50% or less and a desired total fuel cell efficiency of 55% or more. Where fuel cells are operated to have a desired electrical efficiency and a desired total fuel cell efficiency, a solid oxide fuel cell can be operated to have an electrical efficiency of 50% or less with a TFCE of about 55% or more, for example, about 40% EE or less with a TFCE of about 60% or more, about 35% EE or less with a TFCE of about 65% or more, about 30% EE or less with a TCFE of about 70% more, or about 20% EE or less with a TFCE of about 75% or more, or about 15% EE or less with a TFCE of about 80% or more, or about 10% EE or less with a TFCE of about 85% or more.

[0022] In various aspects of the invention, the operation of the fuel cells can be characterized based on a desired total fuel cell productivity ("TFCP") of about 150 mW/cm² or more and a desired total fuel cell efficiency of 55% or more. Where fuel cells are operated to have a desired TFCP above 150 mW/cm² and a desired total fuel cell efficiency, a solid oxide fuel cell can be operated to have a TFCE of about 55% or more, for example, about 60% or more, about 65% or more, about 70% more, or about 75% or more, or about 80% or more, or about 85% or more. When fuel cells are operated to have a desired total fuel cell efficiency of 55% or more, a solid oxide fuel cell can be operated to have a TFCP of at least about 150 mW/cm², or at least about 200 mW/cm², or at least about 250 mW/cm², or at least about 300 mW/cm², or at least about 350 mW/cm². In such aspects, the TFCP can be about 800 mW/cm² or less, or about 700 mW/cm² or less or about 600 mW/cm² or less, or about 500 mW/cm² or less, or about 400 mW/cm² or less.

[0023] In various aspects of the invention, the operation of the fuel cells can be characterized based on a desired total reformable fuel productivity of about 75 mW/cm² or more and a desired total fuel cell efficiency of 55% or more. Where fuel cells are operated to have a desired reformable fuel productivity above about 75 mW/cm² and a desired total fuel cell efficiency, a solid oxide fuel cell can be operated to have a TFCE of about 55% or more, for example, about 60% or more, about 65% or more, about 70% more, or about 75% or more, or about 80% or more, or about 85% or about 90% or more. When fuel cells are operated to have a desired total fuel cell efficiency of 55% or more, a solid oxide fuel cell can be operated to have a reformable

fuel productivity of at least about 75 mW/cm², or at least about 100 mW/cm², or at least about 125 mW/cm², or at least about 150 mW/cm², or at least about 175 mW/cm², or at least about 200 mW/cm² or at least about 300 mW/cm². In such aspects, the reformable fuel productivity can be about 600 mW/cm² or less, or about 500 mW/cm² or less, or about 400 mW/cm² or less, or about 300 mW/cm² or less, or about 200 mW/cm² or less.

[0024] Operating a solid oxide fuel cell to have a desired electrical efficiency, chemical efficiency, and/or total fuel cell efficiency can be achieved in various ways. In some aspects, the chemical efficiency of a solid oxide fuel cell can be increased by increasing the amount of reforming performed within the fuel cell (and/or within an associated reforming stage in a fuel cell assembly) relative to the amount of oxidation of hydrogen in the anode to generate electricity. Conventionally, solid oxide fuel cells have been operated to maximize the efficiency of electrical power generation relative to the amount of fuel consumed while maintaining a suitable heat balance to maintain overall system temperatures. In this type of operating condition, fuel utilizations at the anode of about 70% to about 85% are desirable, in order to maximize electrical efficiency at a desirable (*i.e.*, high) voltage for the electric output and maintain heat balance within the fuel cell. At high fuel utilization values, only a modest amount of hydrogen (or syngas) remains in the anode exhaust for formation of syngas. For example, at about 75% fuel utilization, about 25% of the fuel entering the anode can exit as a combination of syngas and/or unreacted fuel. The modest amount of hydrogen or syngas typically can be enough to maintain sufficient hydrogen concentrations at the anode to facilitate the anode oxidation reaction and to provide enough fuel to heat reactants and/or inlet streams up to appropriate fuel cell operating temperatures.

[0025] In contrast to this conventional operation, a solid oxide fuel cell can be operated at low fuel utilization and higher fuel flow rates, and with little or no recycle of fuel from the anode exhaust to the anode inlet. By operating at low fuel utilization while also reducing or minimizing recycle of fuel to the anode inlet, a larger amount of H₂ and/or CO can be available in the anode exhaust. This excess H₂ and CO can be withdrawn as a syngas product and/or a hydrogen product. In various aspects, the fuel utilization in the fuel cell can be at least about 5%, such as at least about 10% or at least about 15%, or at least about 20%. Additionally or alternately, in a low fuel utilization

aspect, the fuel utilization can be about 60% or less, or about 50% or less, or about 40% or less.

[0026] One option for increasing the chemical efficiency of a fuel cell can be to increase the reformable hydrogen content of fuel delivered to the fuel cell. For example, the reformable hydrogen content of reformable fuel in the input stream delivered to the anode and/or to a reforming stage associated with the anode can be at least about 50% greater than the net amount of hydrogen reacted at the anode, such as at least about 75% greater or at least about 100% greater. Additionally or alternately, the reformable hydrogen content of fuel in the input stream delivered to the anode and/or to a reforming stage associated with the anode can be at least about 50% greater than the net amount of hydrogen reacted at the anode, such as at least about 75% greater or at least about 100% greater. In various aspects, a ratio of the reformable hydrogen content of the reformable fuel in the fuel stream relative to an amount of hydrogen reacted in the anode can be at least about 1.5 : 1, or at least about 2.0 : 1, or at least about 2.5 : 1, or at least about 3.0 : 1. Additionally or alternately, the ratio of reformable hydrogen content of the reformable fuel in the fuel stream relative to the amount of hydrogen reacted in the anode can be about 20 : 1 or less, such as about 15 : 1 or less or about 10 : 1 or less. In one aspect, it is contemplated that less than 100% of the reformable hydrogen content in the anode inlet stream can be converted to hydrogen. For example, at least about 80% of the reformable hydrogen content in an anode inlet stream can be converted to hydrogen in the anode and/or in an associated reforming stage(s), such as at least about 85%, or at least about 90%.

[0027] Either hydrogen or syngas can be withdrawn from the anode exhaust as a chemical energy output. Hydrogen can be used as a clean fuel without generating greenhouse gases when it is burned or combusted. Additionally, hydrogen can be a valuable input for a variety of refinery processes and/or other synthesis processes. Syngas can also be a valuable input for a variety of processes. In addition to having fuel value, syngas can be used as a feedstock for producing other higher value products, such as by using syngas as an input for Fischer-Tropsch synthesis and/or methanol synthesis processes.

[0028] In various aspects, the anode exhaust can have a ratio of H₂ to CO of about 1.5 : 1 to about 10 : 1, such as at least about 3.0 : 1, or at least about 4.0 : 1, or at least

about 5.0 : 1, and/or about 8.0 : 1 or less or about 6.0 : 1 or less. A syngas stream can be withdrawn from the anode exhaust. In various aspects, a syngas stream withdrawn from an anode exhaust can have a ratio of moles of H_2 to moles of CO of at least about 0.9 : 1, such as at least about 1.0 : 1, or at least about 1.2 : 1, or at least about 1.5 : 1, or at least about 1.7 : 1, or at least about 1.8 : 1, or at least about 1.9 : 1. Additionally or alternately, the molar ratio of H_2 to CO in a syngas withdrawn from an anode exhaust can be about 3.0 : 1 or less, such as about 2.7 : 1 or less, or about 2.5 : 1 or less, or about 2.3 : 1 or less, or about 2.2 : 1 or less, or about 2.1 : 1 or less. However, many types of syngas applications benefit from syngas with a molar ratio of H_2 to CO of at least about 1.5 : 1 to about 2.5 : 1 or less, so forming a syngas stream with a molar ratio of H_2 to CO content of, for example, about 1.7 : 1 to about 2.3 : 1 may be desirable for some applications.

[0029] Syngas can be withdrawn from an anode exhaust by any convenient method. In some aspects, syngas can be withdrawn from the anode exhaust by performing separations on the anode exhaust to remove at least a portion of the components in the anode exhaust that are different from H_2 and CO. For example, an anode exhaust can first be passed through an optional water-gas shift stage to adjust the relative amounts of H_2 and CO. One or more separation stages can then be used to remove H_2O and/or CO_2 from the anode exhaust. The remaining portion of the anode exhaust can then correspond to the syngas stream, which can then be withdrawn for use in any convenient manner. Additionally or alternately, the withdrawn syngas stream can be passed through one or more water-gas shift stages and/or passed through one or more separation stages.

[0030] It is noted that an additional or alternative way of modifying the molar ratio of H_2 to CO in the withdrawn syngas can be to separate an H_2 stream from the anode exhaust and/or the syngas, such as by performing a membrane separation. Such a separation to form a separate H_2 output stream can be performed at any convenient location, such as prior to and/or after passing the anode exhaust through a water-gas shift reaction stage, and prior to and/or after passing the anode exhaust through one or more separation stages for removing components in the anode exhaust different from H_2 and CO. Optionally, a water-gas shift stage can be used both before and after separation of an H_2 stream from the anode exhaust. In an additional or alternative

embodiment, H₂ can optionally be separated from the withdrawn syngas stream. In some aspects, a separated H₂ stream can correspond to a high purity H₂ stream, such as an H₂ stream containing at least about 90 vol% of H₂, such as at least about 95 vol% of H₂ or at least about 99 vol% of H₂.

[0031] As an addition, complement, and/or alternative to the fuel cell operating strategies described herein, a solid oxide fuel cell (such as a fuel cell assembly) can be operated with an excess of reformable fuel relative to the amount of hydrogen reacted in the anode of the fuel cell. Instead of selecting the operating conditions of a fuel cell to improve or maximize the electrical efficiency of the fuel cell, an excess of reformable fuel can be passed into the anode of the fuel cell to increase the chemical energy output of the fuel cell. Optionally but preferably, this can lead to an increase in the total efficiency of the fuel cell based on the combined electrical efficiency and chemical efficiency of the fuel cell.

[0032] In some aspects, the reformable hydrogen content of reformable fuel in the input stream delivered to the anode and/or to a reforming stage associated with the anode can be at least about 50% greater than the amount of hydrogen oxidized in the anode, such as at least about 75% greater or at least about 100% greater. In various aspects, a ratio of the reformable hydrogen content of the reformable fuel in the fuel stream relative to an amount of hydrogen reacted in the anode can be at least about 1.5 : 1, or at least about 2.0 : 1, or at least about 2.5 : 1, or at least about 3.0 : 1.

Additionally or alternately, the ratio of reformable hydrogen content of the reformable fuel in the fuel stream relative to the amount of hydrogen reacted in the anode can be about 20 : 1 or less, such as about 15 : 1 or less or about 10 : 1 or less. In one aspect, it is contemplated that less than 100% of the reformable hydrogen content in the anode inlet stream can be converted to hydrogen. For example, at least about 80% of the reformable hydrogen content in an anode inlet stream can be converted to hydrogen in the anode and/or in an associated reforming stage, such as at least about 85%, or at least about 90%.

[0033] Additionally or alternately, the amount of reformable fuel delivered to the anode can be characterized based on the Lower Heating Value (LHV) of the reformable fuel relative to the LHV of the hydrogen oxidized in the anode. This can be referred to as a reformable fuel surplus ratio. In such an alternative, the reformable fuel surplus

ratio can be at least about 2.0, such as at least about 2.5, or at least about 3.0, or at least about 4.0. Additionally or alternately, the reformable fuel surplus ratio can be about 25.0 or less, such as about 20.0 or less, or about 15.0 or less, or about 10.0 or less.

[0034] In various aspects of the invention, the operation of the fuel cells can be characterized based on a desired total fuel cell productivity ("TFCP") of at least about 150 mW/cm^2 and a desired reformable fuel surplus ratio. For example, a solid oxide fuel cell can be operated to have a TFCP of at least about 150 mW/cm^2 and a reformable fuel surplus ratio of at least about 2.0, such as at least about 2.5, or at least about 3.0, or at least about 4.0. Additionally or alternately, the TFCP can be above about 150 mW/cm^2 and the reformable fuel surplus ratio can be about 25.0 or less, such as about 20.0 or less, or about 15.0 or less, or about 10.0 or less. When fuel cells are operated to have a reformable fuel surplus ratio of at least about 2.0, a solid oxide fuel cell can be operated to have a TFCP of at least about 150 mW/cm^2 , or at least about 200 mW/cm^2 , or at least about 250 mW/cm^2 , or at least about 300 mW/cm^2 , or at least about 350 mW/cm^2 . In such aspects, the TFCP can be about 800 mW/cm^2 or less, or about 700 mW/cm^2 or less or about 600 mW/cm^2 or less, or about 500 mW/cm^2 or less, or about 400 mW/cm^2 or less.

[0035] In various aspects of the invention, the operation of the fuel cells can be characterized based on a desired total reformable fuel productivity of about 75 mW/cm^2 or more and a desired a reformable fuel surplus ratio. In some aspects, fuel cells can be operated to have a desired reformable fuel productivity above about 75 mW/cm^2 and a reformable fuel surplus ratio of at least about 2.0, such as at least about 2.5, or at least about 3.0, or at least about 4.0. Additionally or alternately, the total reformable fuel productivity can be above about 75 mW/cm^2 and the reformable fuel surplus ratio can be about 25.0 or less, such as about 20.0 or less, or about 15.0 or less, or about 10.0 or less. When fuel cells are operated to have a reformable fuel surplus ratio of at least about 2.0, a solid oxide fuel cell can be operated to have a reformable fuel productivity of at least about 75 mW/cm^2 , or at least about 100 mW/cm^2 , or at least about 125 mW/cm^2 , or at least about 150 mW/cm^2 , or at least about 175 mW/cm^2 , or at least about 200 mW/cm^2 or at least about 300 mW/cm^2 . In such aspects, the reformable fuel productivity can be about 600 mW/cm^2 or less, or about 500 mW/cm^2 or less, or about 400 mW/cm^2 or less, or about 300 mW/cm^2 or less, or about 200 mW/cm^2 or less.

[0036] As an addition, complement, and/or alternative to the fuel cell operating strategies described herein, a solid oxide fuel cell can be operated so that the amount of reforming can be selected relative to the amount of oxidation in order to achieve a desired thermal ratio for the fuel cell. As used herein, the “thermal ratio” is defined as the heat produced by exothermic reactions in a fuel cell assembly divided by the endothermic heat demand of reforming reactions occurring within the fuel cell assembly. Expressed mathematically, the thermal ratio (TH) = Q_{EX}/Q_{EN} , where Q_{EX} is the sum of heat produced by exothermic reactions and Q_{EN} is the sum of heat consumed by the endothermic reactions occurring within the fuel cell. Note that the heat produced by the exothermic reactions corresponds to any heat due to reforming reactions, water gas shift reactions, and the electrochemical reactions in the cell. The heat generated by the electrochemical reactions can be calculated based on the ideal electrochemical potential of the fuel cell reaction across the electrolyte minus the actual output voltage of the fuel cell. For example, the ideal electrochemical potential of the reaction in a SOFC is believed to be about 1.04V based on the net reaction that occurs in the cell. During operation of the SOFC, the cell will typically have an output voltage less than 1.1 V due to various losses. For example, a common output/operating voltage can be about 0.65 V, or about 0.7 V, or about 0.75 V, or about 0.8V. The heat generated is equal to the electrochemical potential of the cell (e.g., ~1.04V) minus the operating voltage. For example, the heat produced by the electrochemical reactions in the cell is ~0.34 V when the output voltage of ~0.7V. Thus, in this scenario, the electrochemical reactions would produce ~0.7 V of electricity and ~0.34 V of heat energy. In such an example, the ~0.7 V of electrical energy is not included as part of Q_{EX} . In other words, heat energy is not electrical energy.

[0037] In various aspects, the operating parameters of the SOFC can be set to achieve an operating voltage below at least 0.7 V, such as at least below 0.65 V, or such as at least below 0.6 V, or such as at least below 0.5V, or such as at least below 0.4 V, or such as at least below 0.3 V.

[0038] In various aspects, a thermal ratio can be determined for any convenient fuel cell structure, such as a fuel cell stack, an individual fuel cell within a fuel cell stack, a fuel cell stack with an integrated reforming stage, a fuel cell stack with an integrated endothermic reaction stage, or a combination thereof. The thermal ratio may also be

calculated for different units within a fuel cell stack, such as an assembly of fuel cells or fuel cell stacks. For example, the thermal ratio may be calculated for a single anode within a single fuel cell, an anode section within a fuel cell stack, or an anode section within a fuel cell stack along with integrated reforming stages and/or integrated endothermic reaction stage elements in sufficiently close proximity to the anode section to be integrated from a heat integration standpoint. As used herein, "an anode section" comprises anodes within a fuel cell stack that share a common inlet or outlet manifold.

[0039] In various aspects of the invention, the operation of the fuel cells can be characterized based on a thermal ratio. Where fuel cells are operated to have a desired thermal ratio, a solid oxide fuel cell can be operated to have a thermal ratio of about 1.5 or less, for example about 1.3 or less, or about 1.15 or less, or about 1.0 or less, or about 0.95 or less, or about 0.90 or less, or about 0.85 or less, or about 0.80 or less, or about 0.75 or less. Additionally or alternately, the thermal ratio can be at least about 0.25, or at least about 0.35, or at least about 0.45, or at least about 0.50.

[0040] In various aspects of the invention, the operation of the fuel cells can be characterized based on a desired total reformable fuel productivity of about 75 mW/cm² or more and a desired thermal ratio. In some aspects, fuel cells can be operated to have a desired reformable fuel productivity above about 75 mW/cm² and a thermal ratio of about 1.5 or less, for example about 1.3 or less, or about 1.15 or less, or about 1.0 or less, or about 0.95 or less, or about 0.90 or less, or about 0.85 or less, or about 0.80 or less, or about 0.75 or less. Additionally or alternately, the total reformable fuel productivity can be above about 75 mW/cm² and the thermal ratio can be at least about 0.25, or at least about 0.35, or at least about 0.45, or at least about 0.50. When fuel cells are operated to have a thermal ratio of about 0.25 to about 1.3, a solid oxide fuel cell can be operated to have a reformable fuel productivity of at least about 75 mW/cm², or at least about 100 mW/cm², or at least about 125 mW/cm², or at least about 150 mW/cm², or at least about 175 mW/cm², or at least about 200 mW/cm² or at least about 300 mW/cm². In such aspects, the reformable fuel productivity can be about 600 mW/cm² or less, or about 500 mW/cm² or less, or about 400 mW/cm² or less, or about 300 mW/cm² or less, or about 200 mW/cm² or less.

[0041] In various aspects of the invention, the operation of the fuel cells can be characterized based on a desired total fuel cell productivity of about 150 mW/cm² or

more and a desired a thermal ratio. In one aspects, fuel cells are operated to have a desired total fuel cell productivity above about 150 mW/cm^2 and a thermal ratio of about 1.5 or less, for example about 1.3 or less, or about 1.15 or less, or about 1.0 or less, or about 0.95 or less, or about 0.90 or less, or about 0.85 or less, or about 0.80 or less, or about 0.75 or less. Additionally or alternately, the total fuel cell productivity can be above about 150 mW/cm^2 and the thermal ratio can be at least about 0.25, or at least about 0.35, or at least about 0.45, or at least about 0.50. When fuel cells are operated to have a thermal ratio of about 0.25 to about 1.3, a solid oxide fuel cell can be operated to have a TFCP of at least about 150 mW/cm^2 , or at least about 200 mW/cm^2 , or at least about 250 mW/cm^2 , or at least about 300 mW/cm^2 , or at least about 350 mW/cm^2 . In such aspects, the TFCP can be about 800 mW/cm^2 or less, or about 700 mW/cm^2 or less or about 600 mW/cm^2 or less, or about 500 mW/cm^2 or less, or about 400 mW/cm^2 or less.

[0042] Additionally or alternately, in some aspects the fuel cell can be operated to have a temperature rise between anode input and anode output of about 40°C or less, such as about 20°C or less, or about 10°C or less. Further additionally or alternately, the fuel cell can be operated to have an anode outlet temperature that is from about 10°C lower to about 10°C higher than the temperature of the anode inlet. Still further additionally or alternately, the fuel cell can be operated to have an anode inlet temperature that is greater than the anode outlet temperature, such as at least about 5°C greater, or at least about 10°C greater, or at least about 20°C greater, or at least about 25°C greater. Yet still further additionally or alternately, the fuel cell can be operated to have an anode inlet temperature that is greater than the anode outlet temperature by about 100°C or less, such as by about 80°C or less, or about 60°C or less, or about 50°C or less, or about 40°C or less, or about 30°C or less, or about 20°C or less, or about 10°C or less. Minimizing the difference between the anode inlet temperature and outlet temperature may help maintain mechanical integrity of the ceramic components in the solid oxide fuel cell.

[0043] As an addition, complement, and/or alternative to the fuel cell operating strategies described herein, a solid oxide fuel cell (such as a fuel cell assembly) can be operated at conditions that can provide increased power density. The power density of a fuel cell corresponds to the actual operating voltage V_A multiplied by the current

density I . For a solid oxide fuel cell operating at a voltage V_A , the fuel cell also can tend to generate waste heat, the waste heat defined as $(V_0 - V_A) \cdot I$ based on the differential between V_A and the ideal voltage V_0 for a fuel cell providing current density I . A portion of this waste heat can be consumed by reforming of a reformable fuel within the anode of the fuel cell. The remaining portion of this waste heat can be absorbed by the surrounding fuel cell structures and gas flows, resulting in a temperature differential across the fuel cell. Under conventional operating conditions, the power density of a fuel cell can be limited based on the amount of waste heat that the fuel cell can tolerate without compromising the integrity of the fuel cell.

[0044] In various aspects, the amount of waste heat that a fuel cell can tolerate can be increased by performing an effective amount of an endothermic reaction within the fuel cell. One example of an endothermic reaction includes steam reforming of a reformable fuel within a fuel cell anode and/or in an associated reforming stage, such as an integrated reforming stage in a fuel cell stack. By providing additional reformable fuel to the anode of the fuel cell (or to an integrated / associated reforming stage), additional reforming can be performed so that additional waste heat can be consumed. This can reduce the amount of temperature differential across the fuel cell, thus allowing the fuel cell to operate under an operating condition with an increased amount of waste heat. The loss of electrical efficiency can be offset by the creation of an additional product stream, such as syngas and/or H_2 , that can be used for various purposes including additional electricity generation further expanding the power range of the system.

[0045] In various aspects, the amount of waste heat generated by a fuel cell, $(V_0 - V_A) \cdot I$ as defined above, can be at least about 30 mW/cm², such as at least about 40 mW/cm², or at least about 50 mW/cm², or at least about 60 mW/cm², or at least about 70 mW/cm², or at least about 80 mW/cm², or at least about 100 mW/cm², or at least about 120 mW/cm², or at least about 140 mW/cm², or at least about 160 mW/cm², or at least about 180 mW/cm², or at least about 200 mW/cm², or at least about 220 mW/cm², or at least about 250 mW/cm², or at least about 300 mW/cm². Additionally or alternately, the amount of waste heat generated by a fuel cell can be less than about 400 mW/cm², such as less than about 300 mW/cm², or less than about 200 mW/cm², or less than about 175 mW/cm², or less than about 150 mW/cm².

[0046] Although the amount of waste heat being generated can be relatively high, such waste heat may not necessarily represent operating a fuel cell with poor efficiency. Instead, the waste heat can be generated due to operating a fuel cell at an increased power density. Part of improving the power density of a fuel cell can include operating the fuel cell at a sufficiently high current density. In various aspects, the current density generated by the fuel cell can be at least about 150 mA/cm², such as at least about 160 mA/cm², or at least about 170 mA/cm², or at least about 180 mA/cm², or at least about 190 mA/cm², or at least about 200 mA/cm², or at least about 300 mA/cm², or at least about 400 mA/cm², or at least about 800 mA/cm². Additionally or alternately, the current density generated by the fuel cell can be about 800 mA/cm² or less, such as 450 mA/cm², or less, or 300 mA/cm², or less or 250 mA/cm², or less or 200 mA/cm² or less.

[0047] In various aspects, to allow a fuel cell to be operated with increased power generation and increased generation of waste heat, an effective amount of an endothermic reaction (such as a reforming reaction) can be performed. Alternatively, other endothermic reactions unrelated to anode operations can be used to utilize the waste heat by interspersing “plates” or stages into the fuel cell array in thermal communication but not in fluid communication with either anodes or cathodes. The effective amount of the endothermic reaction can be performed in an associated reforming stage, an integrated reforming stage, an integrated stack element for performing an endothermic reaction, or a combination thereof. The effective amount of the endothermic reaction can correspond to an amount sufficient to reduce the temperature rise from the fuel cell inlet to the fuel cell outlet to about 100°C or less, such as about 90°C or less, or about 80°C or less, or about 70°C or less, or about 60°C or less, or about 50°C or less, or about 40°C or less, or about 30°C or less. Additionally or alternately, the effective amount of the endothermic reaction can correspond to an amount sufficient to cause a temperature decrease from the fuel cell inlet to the fuel cell outlet of about 100°C or less, such as about 90°C or less, or about 80°C or less, or about 70°C or less, or about 60°C or less, or about 50°C or less, or about 40°C or less, or about 30°C or less, or about 20°C or less, or about 10°C or less. A temperature decrease from the fuel cell inlet to the fuel cell outlet can occur when the effective amount of the endothermic reaction exceeds the waste heat generated.

Additionally or alternately, this can correspond to having the endothermic reaction(s) (such as a combination of reforming and another endothermic reaction) consume at least about 40% of the waste heat generated by the fuel cell, such as consuming at least about 50% of the waste heat, or at least about 60% of the waste heat, or at least about 75% of the waste heat. Further additionally or alternately, the endothermic reaction(s) can consume about 95% of the waste heat or less, such as about 90% of the waste heat or less, or about 85% of the waste heat or less.

Additional Definitions

[0048] Syngas: In this description, syngas is defined as mixture of H_2 and CO in any ratio. Optionally, H_2O and/or CO_2 may be present in the syngas. Optionally, inert compounds (such as nitrogen) and residual reformable fuel compounds may be present in the syngas. If components other than H_2 and CO are present in the syngas, the combined volume percentage of H_2 and CO in the syngas can be at least 25 vol% relative to the total volume of the syngas, such as at least 40 vol%, or at least 50 vol%, or at least 60 vol%. Additionally or alternately, the combined volume percentage of H_2 and CO in the syngas can be 100 vol% or less, such as 95 vol% or less or 90 vol% or less.

[0049] Reformable fuel: A reformable fuel is defined as a fuel that contains carbon-hydrogen bonds that can be reformed to generate H_2 . Hydrocarbons are examples of reformable fuels, as are other hydrocarbonaceous compounds such as alcohols. Although CO and H_2O can participate in a water gas shift reaction to form hydrogen, CO is not considered a reformable fuel under this definition.

[0050] Reformable hydrogen content: The reformable hydrogen content of a fuel is defined as the number of H_2 molecules that can be derived from a fuel by reforming the fuel and then driving the water gas shift reaction to completion to maximize H_2 production. It is noted that H_2 by definition has a reformable hydrogen content of 1, although H_2 itself is not defined as a reformable fuel herein. Similarly, CO has a reformable hydrogen content of 1. Although CO is not strictly reformable, driving the water gas shift reaction to completion will result in exchange of a CO for an H_2 . As examples of reformable hydrogen content for reformable fuels, the reformable hydrogen content of methane is 4 H_2 molecules while the reformable hydrogen content of ethane is 7 H_2 molecules. More generally, if a fuel has the composition $C_xH_yO_z$,

then the reformable hydrogen content of the fuel at 100% reforming and water-gas shift is $n(\text{H}_2 \text{ max reforming}) = 2x + y/2 - z$. Based on this definition, fuel utilization within a cell can then be expressed as $n(\text{H}_2 \text{ ox})/n(\text{H}_2 \text{ max reforming})$. Of course, the reformable hydrogen content of a mixture of components can be determined based on the reformable hydrogen content of the individual components. The reformable hydrogen content of compounds that contain other heteroatoms, such as oxygen, sulfur or nitrogen, can also be calculated in a similar manner.

[0051] Oxidation Reaction: In this discussion, the oxidation reaction within the anode of a fuel cell is defined as the reaction corresponding to oxidation of H_2 by reaction with O^{2-} to form H_2O . It is noted that the reforming reaction within the anode, where a compound containing a carbon-hydrogen bond is converted into H_2 and CO or CO_2 , is excluded from this definition of the oxidation reaction in the anode. The water-gas shift reaction is similarly outside of this definition of the oxidation reaction. It is further noted that references to a combustion reaction are defined as references to reactions where H_2 or a compound containing carbon-hydrogen bond(s) are reacted with O_2 to form H_2O and carbon oxides in a non-electrochemical burner, such as the combustion zone of a combustion-powered generator.

[0052] Aspects of the invention can adjust anode fuel parameters to achieve a desired operating range for the fuel cell. Anode fuel parameters can be characterized directly, and/or in relation to other fuel cell processes in the form of one or more ratios. For example, the anode fuel parameters can be controlled to achieve one or more ratios including a fuel utilization, a fuel cell heating value utilization, a fuel surplus ratio, a reformable fuel surplus ratio, a reformable hydrogen content fuel ratio, and combinations thereof.

[0053] Fuel utilization: Fuel utilization is an option for characterizing operation of the anode based on the amount of oxidized fuel relative to the reformable hydrogen content of an input stream can be used to define a fuel utilization for a fuel cell. In this discussion, “fuel utilization” is defined as the ratio of the amount of hydrogen oxidized in the anode for production of electricity (as described above) versus the reformable hydrogen content of the anode input (including any associated reforming stages). Reformable hydrogen content has been defined above as the number of H_2 molecules that can be derived from a fuel by reforming the fuel and then driving the water gas

shift reaction to completion to maximize H₂ production. For example, each methane introduced into an anode and exposed to steam reforming conditions results in generation of the equivalent of 4 H₂ molecules at max production. (Depending on the reforming and/or anode conditions, the reforming product can correspond to a non-water gas shifted product, where one or more of the H₂ molecules is present instead in the form of a CO molecule.) Thus, methane is defined as having a reformable hydrogen content of 4 H₂ molecules. As another example, under this definition ethane has a reformable hydrogen content of 7 H₂ molecules.

[0054] The utilization of fuel in the anode can also be characterized by defining a heating value utilization based on a ratio of the Lower Heating Value of hydrogen oxidized in the anode due to the fuel cell anode reaction relative to the Lower Heating Value of all fuel delivered to the anode and/or a reforming stage associated with the anode. The “fuel cell heating value utilization” as used herein can be computed using the flow rates and Lower Heating Value (LHV) of the fuel components entering and leaving the fuel cell anode. As such, fuel cell heating value utilization can be computed as $(\text{LHV}(\text{anode_in}) - \text{LHV}(\text{anode_out})) / \text{LHV}(\text{anode_in})$, where LHV(anode_in) and LHV(anode_out) refer to the LHV of the fuel components (such as H₂, CH₄, and/or CO) in the anode inlet and outlet streams or flows, respectively. In this definition, the LHV of a stream or flow may be computed as a sum of values for each fuel component in the input and/or output stream. The contribution of each fuel component to the sum can correspond to the fuel component’s flow rate (*e.g.*, mol/hr) multiplied by the fuel component’s LHV (*e.g.*, joules/mol).

[0055] Lower Heating Value: The lower heating value is defined as the enthalpy of combustion of a fuel component to vapor phase, fully oxidized products (*e.g.*, vapor phase CO₂ and H₂O product). For example, any CO₂ present in an anode input stream does not contribute to the fuel content of the anode input, since CO₂ is already fully oxidized. For this definition, the amount of oxidation occurring in the anode due to the anode fuel cell reaction is defined as oxidation of H₂ in the anode as part of the electrochemical reaction in the anode, as defined above.

[0056] It is noted that, for the special case where the only fuel in the anode input flow is H₂, the only reaction involving a fuel component that can take place in the anode represents the conversion of H₂ into H₂O. In this special case, the fuel utilization

simplifies to $(\text{H}_2\text{-rate-in} - \text{H}_2\text{-rate-out})/\text{H}_2\text{-rate-in}$. In such a case, H_2 would be the only fuel component, and so the H_2 LHV would cancel out of the equation. In the more general case, the anode feed may contain, for example, CH_4 , H_2 , and CO in various amounts. Because these species can typically be present in different amounts in the anode outlet, the summation as described above can be needed to determine the fuel utilization.

[0057] Alternatively or in addition to fuel utilization, the utilization for other reactants in the fuel cell can be characterized. For example, the operation of a fuel cell can additionally or alternately be characterized with regard to “oxidant” utilization. The values for oxidant utilization can be specified in a similar manner.

[0058] Fuel surplus ratio: Still another way to characterize the reactions in a solid oxide fuel cell is by defining a utilization based on a ratio of the Lower Heating Value of all fuel delivered to the anode and/or a reforming stage associated with the anode relative to the Lower Heating Value of hydrogen oxidized in the anode due to the fuel cell anode reaction. This quantity will be referred to as a fuel surplus ratio. As such the fuel surplus ratio can be computed as $(\text{LHV}(\text{anode_in}) / (\text{LHV}(\text{anode_in}) - \text{LHV}(\text{anode_out})))$ where $\text{LHV}(\text{anode_in})$ and $\text{LHV}(\text{anode_out})$ refer to the LHV of the fuel components (such as H_2 , CH_4 , and/or CO) in the anode inlet and outlet streams or flows, respectively. In various aspects of the invention, a solid oxide fuel cell can be operated to have a fuel surplus ratio of at least about 1.0, such as at least about 1.5, or at least about 2.0, or at least about 2.5, or at least about 3.0, or at least about 4.0. Additionally or alternately, the fuel surplus ratio can be about 25.0 or less.

[0059] It is noted that not all of the reformable fuel in the input stream for the anode may be reformed. Preferably, at least about 90% of the reformable fuel in the input stream to the anode (and/or into an associated reforming stage) can be reformed prior to exiting the anode, such as at least about 95% or at least about 98%. In some alternative aspects, the amount of reformable fuel that is reformed can be from about 75% to about 90%, such as at least about 80%.

[0060] The above definition for fuel surplus ratio provides a method for characterizing the amount of reforming occurring within the anode and/or reforming stage(s) associated with a fuel cell relative to the amount of fuel consumed in the fuel cell anode for generation of electric power.

[0061] Optionally, the fuel surplus ratio can be modified to account for situations where fuel is recycled from the anode output to the anode input. When fuel (such as H₂, CO, and/or unreformed or partially reformed hydrocarbons) is recycled from anode output to anode input, such recycled fuel components do not represent a surplus amount of reformable or reformed fuel that can be used for other purposes. Instead, such recycled fuel components merely indicate a desire to reduce fuel utilization in a fuel cell.

[0062] **Reformable fuel surplus ratio:** Calculating a reformable fuel surplus ratio is one option to account for such recycled fuel components is to narrow the definition of surplus fuel, so that only the LHV of reformable fuels is included in the input stream to the anode. As used herein the “reformable fuel surplus ratio” is defined as the Lower Heating Value of reformable fuel delivered to the anode and/or a reforming stage associated with the anode relative to the Lower Heating Value of hydrogen oxidized in the anode due to the fuel cell anode reaction. Under the definition for reformable fuel surplus ratio, the LHV of any H₂ or CO in the anode input is excluded. Such an LHV of reformable fuel can still be measured by characterizing the actual composition entering a fuel cell anode, so no distinction between recycled components and fresh components needs to be made. Although some non-reformed or partially reformed fuel may also be recycled, in most aspects the majority of the fuel recycled to the anode can correspond to reformed products such as H₂ or CO. Expressed mathematically, the reformable fuel surplus ratio (R_{RFS}) = LHV_{RF} / LHV_{OH} , where LHV_{RF} is the Lower Heating Value (LHV) of the reformable fuel and LHV_{OH} is the Lower Heating Value (LHV) of the hydrogen oxidized in the anode. The LHV of the hydrogen oxidized in the anode may be calculated by subtracting the LHV of the anode outlet stream from the LHV of the anode inlet stream (*e.g.*, $LHV(\text{anode_in}) - LHV(\text{anode_out})$). In various aspects of the invention, a solid oxide fuel cell can be operated to have a reformable fuel surplus ratio of at least about 0.25, such as at least about 0.5, or at least about 1.0, or at least about 1.5, or at least about 2.0, or at least about 2.5, or at least about 3.0, or at least about 4.0. Additionally or alternately, the reformable fuel surplus ratio can be about 25.0 or less. It is noted that this narrower definition based on the amount of reformable fuel delivered to the anode relative to the amount of oxidation in the anode can distinguish between two types of fuel cell operation methods that have low fuel

utilization. Some fuel cells achieve low fuel utilization by recycling a substantial portion of the anode output back to the anode input. This recycle can allow any hydrogen in the anode input to be used again as an input to the anode. This can reduce the amount of reforming, as even though the fuel utilization is low for a single pass through the fuel cell, at least a portion of the unused fuel is recycled for use in a later pass. Thus, fuel cells with a wide variety of fuel utilization values may have the same ratio of reformable fuel delivered to the anode reforming stage(s) versus hydrogen oxidized in the anode reaction. In order to change the ratio of reformable fuel delivered to the anode reforming stages relative to the amount of oxidation in the anode, either an anode feed with a native content of non-reformable fuel needs to be identified, or unused fuel in the anode output needs to be withdrawn for other uses, or both.

[0063] Reformable hydrogen surplus ratio: Still another option for characterizing the operation of a fuel cell is based on a “reformable hydrogen surplus ratio.” The reformable fuel surplus ratio defined above is defined based on the lower heating value of reformable fuel components. The reformable hydrogen surplus ratio is defined as the reformable hydrogen content of reformable fuel delivered to the anode and/or a reforming stage associated with the anode relative to the hydrogen reacted in the anode due to the fuel cell anode reaction. As such, the “reformable hydrogen surplus ratio” can be computed as $(\text{RFC}(\text{reformable_anode_in}) / (\text{RFC}(\text{reformable_anode_in}) - \text{RFC}(\text{anode_out})))$, where $\text{RFC}(\text{reformable_anode_in})$ refers to the reformable hydrogen content of reformable fuels in the anode inlet streams or flows, while $\text{RFC}(\text{anode_out})$ refers to the reformable hydrogen content of the fuel components (such as H_2 , CH_4 , and/or CO) in the anode inlet and outlet streams or flows. The RFC can be expressed in moles/s, moles/hr, or similar. An example of a method for operating a fuel cell with a large ratio of reformable fuel delivered to the anode reforming stage(s) versus amount of oxidation in the anode can be a method where excess reforming is performed in order to balance the generation and consumption of heat in the fuel cell. Reforming a reformable fuel to form H_2 and CO is an endothermic process. This endothermic reaction can be countered by the generation of electrical current in the fuel cell, which can also produce excess heat corresponding (roughly) to the difference between the amount of heat generated by the anode oxidation reaction and the cathode reaction and the energy that exits the fuel cell in the form of electric current. The excess heat per

mole of hydrogen involved in the anode oxidation reaction / cathode reaction can be greater than the heat absorbed to generate a mole of hydrogen by reforming. As a result, a fuel cell operated under conventional conditions can exhibit a temperature increase from inlet to outlet. Instead of this type of conventional operation, the amount of fuel reformed in the reforming stages associated with the anode can be increased. For example, additional fuel can be reformed so that the heat generated by the exothermic fuel cell reactions can be (roughly) balanced by the heat consumed in reforming, or even the heat consumed by reforming can be beyond the excess heat generated by the fuel oxidation, resulting in a temperature drop across the fuel cell. This can result in a substantial excess of hydrogen relative to the amount needed for electrical power generation. As one example, a feed to the anode inlet of a fuel cell or an associated reforming stage can be substantially composed of reformable fuel, such as a substantially pure methane feed. During conventional operation for electric power generation using such a fuel, a solid oxide fuel cell can be operated with a fuel utilization of about 75%. This means that about 75% (or $\frac{3}{4}$) of the fuel content delivered to the anode is used to form hydrogen that is then reacted in the anode with oxygen ions to form H_2O . In conventional operation, the remaining about 25% of the fuel content can be reformed to H_2 within the fuel cell (or can pass through the fuel cell unreacted for any CO or H_2 in the fuel), and then combusted outside of the fuel cell to form H_2O to provide heat for the cathode inlet to the fuel cell. The reformable hydrogen surplus ratio in this situation can be $4/(4-1) = 4/3$.

[0064] Electrical efficiency: As used herein, the term “electrical efficiency” (“EE”) is defined as the electrochemical power produced by the fuel cell divided by the rate of Lower Heating Value (“LHV”) of fuel input to the fuel cell. The fuel inputs to the fuel cell includes both fuel delivered to the anode as well as any fuel used to maintain the temperature of the fuel cell, such as fuel delivered to a burner associated with a fuel cell. In this description, the power produced by the fuel may be described in terms of LHV(el) fuel rate.

[0065] Electrochemical power: As used herein, the term “electrochemical power” or LHV(el) is the power generated by the circuit connecting the cathode to the anode in the fuel cell and the transfer of oxygen ions across the fuel cell’s electrolyte. Electrochemical power excludes power produced or consumed by equipment upstream

or downstream from the fuel cell. For example, electricity produced from heat in a fuel cell exhaust stream is not considered part of the electrochemical power. Similarly, power generated by a gas turbine or other equipment upstream of the fuel cell is not part of the electrochemical power generated. The “electrochemical power” does not take electrical power consumed during operation of the fuel cell into account, or any loss incurred by conversion of the direct current to alternating current. In other words, electrical power used to supply the fuel cell operation or otherwise operate the fuel cell is not subtracted from the direct current power produced by the fuel cell. As used herein, the power density is the current density multiplied by voltage. As used herein, the total fuel cell power is the power density multiplied by the fuel cell area.

[0066] Fuel inputs: As used herein, the term “anode fuel input,” designated as $LHV(anode_in)$, is the amount of fuel within the anode inlet stream. The term “fuel input”, designated as $LHV(in)$, is the total amount of fuel delivered to the fuel cell, including both the amount of fuel within the anode inlet stream and the amount of fuel used to maintain the temperature of the fuel cell. The fuel may include both reformable and nonreformable fuels, based on the definition of a reformable fuel provided herein. Fuel input is not the same as fuel utilization.

[0067] Total fuel cell efficiency: As used herein, the term “total fuel cell efficiency” (“TFCE”) is defined as: the electrochemical power generated by the fuel cell, plus the rate of LHV of syngas produced by the fuel cell, divided by the rate of LHV of fuel input to the anode. In other words, $TFCE = (LHV(el) + LHV(sg\ net))/LHV(anode_in)$, where $LHV(anode_in)$ refers to rate at which the LHV of the fuel components (such as H_2 , CH_4 , and/or CO) delivered to the anode and $LHV(sg\ net)$ refers to a rate at which syngas (H_2 , CO) is produced in the anode, which is the difference between syngas input to the anode and syngas output from the anode. $LHV(el)$ describes the electrochemical power generation of the fuel cell. The total fuel cell efficiency excludes heat generated by the fuel cell that is put to beneficial use outside of the fuel cell. In operation, heat generated by the fuel cell may be put to beneficial use by downstream equipment. For example, the heat may be used to generate additional electricity or to heat water. These uses, when they occur apart from the fuel cell, are not part of the total fuel cell efficiency, as the term is used in this application. The total fuel cell efficiency is for the

fuel cell operation only, and does not include power production, or consumption, upstream, or downstream, of the fuel cell.

[0068] Chemical efficiency: As used herein, the term “chemical efficiency”, is defined as the lower heating value of H₂ and CO in the anode exhaust of the fuel cell, or LHV(sg out), divided by the fuel input, or LHV(in).

[0069] Neither the electrical efficiency nor the total system efficiency takes the efficiency of upstream or downstream processes into consideration. For example, it may be advantageous to use turbine exhaust as a source of O₂ for the fuel cell cathode. In this arrangement, the efficiency of the turbine is not considered as part of the electrical efficiency or the total fuel cell efficiency calculation. Similarly, outputs from the fuel cell may be recycled as inputs to the fuel cell. A recycle loop is not considered when calculating electrical efficiency or the total fuel cell efficiency in single pass mode.

[0070] Syngas produced: As used herein, the term “syngas produced” is the difference between syngas input to the anode and syngas output from the anode. Syngas may be used as an input, or fuel, for the anode, at least in part. For example, a system may include an anode recycle loop that returns syngas from the anode exhaust to the anode inlet where it is supplemented with natural gas or other suitable fuel. Syngas produced LHV (sg net) = (LHV(sg out) - LHV(sg in)), where LHV(sg in) and LHV(sg out) refer to the LHV of the syngas in the anode inlet and syngas in the anode outlet streams or flows, respectively. It is noted that at least a portion of the syngas produced by the reforming reactions within an anode can typically be utilized in the anode to produce electricity. The hydrogen utilized to produce electricity is not included in the definition of “syngas produced” because it does not exit the anode. As used herein, the term “syngas ratio” is the LHV of the net syngas produced divided by the LHV of the fuel input to the anode or LHV (sg net)/LHV(anode in). Molar flow rates of syngas and fuel can be used instead of LHV to express a molar-based syngas ratio and a molar-based syngas produced.

[0071] Steam to carbon ratio (S/C): As used herein, the steam to carbon ratio (S/C) is the molar ratio of steam in a flow to reformable carbon in the flow. Carbon in the form of CO and CO₂ are not included as reformable carbon in this definition. The steam to carbon ratio can be measured and/or controlled at different points in the

system. For example, the composition of an anode inlet stream can be manipulated to achieve a S/C that is suitable for reforming in the anode. The S/C can be given as the molar flow rate of H₂O divided by the product of the molar flow rate of fuel multiplied by the number of carbon atoms in the fuel, *e.g.*, one for methane. Thus, $S/C = f_{H_2O} / (f_{CH_4} \times \#C)$, where f_{H_2O} is the molar flow rate of water, where f_{CH_4} is the molar flow rate of methane (or other fuel) and #C is the number of carbons in the fuel. In various aspects, the S/C can be about 2, or about 1 to 3, or about 0.5 to 5. It can be desirable to provide only enough steam to satisfy the reforming reaction's stoichiometry and prevent fouling, as excess steam dilutes the anode reactants and costs energy to produce.

[0072] Fuel Cell and Fuel Cell Components: In this discussion, a fuel cell can correspond to a single cell, with an anode and a cathode separated by an electrolyte. Solid Oxide Fuel Cells can take either a planar form or tubular form. As used herein, a fuel cell can refer to either or both forms. The anode and cathode can receive input gas flows to facilitate the respective anode and cathode reactions for transporting charge across the electrolyte and generating electricity. A fuel cell stack can represent a plurality of cells in an integrated unit. Although a fuel cell stack can include multiple fuel cells, the fuel cells can typically be connected in parallel and can function (approximately) as if they collectively represented a single fuel cell of a larger size. When an input flow is delivered to the anode or cathode of a fuel cell stack, the fuel stack can include flow channels for dividing the input flow between each of the cells in the stack and flow channels for combining the output flows from the individual cells. In this discussion, a fuel cell array can be used to refer to a plurality of fuel cells (such as a plurality of fuel cell stacks) that are arranged in series, in parallel, or in any other convenient manner (*e.g.*, in a combination of series and parallel). A fuel cell array can include one or more stages of fuel cells and/or fuel cell stacks, where the anode/cathode output from a first stage may serve as the anode/cathode input for a second stage. It is noted that the anodes in a fuel cell array do not have to be connected in the same way as the cathodes in the array. For convenience, the input to the first anode stage of a fuel cell array may be referred to as the anode input for the array, and the input to the first cathode stage of the fuel cell array may be referred to as the cathode input to the array. Similarly, the output from the final anode/cathode stage may be referred to as the anode/cathode output from the array.

[0073] It should be understood that reference to use of a fuel cell herein typically denotes a “fuel cell stack” composed of individual fuel cells, and more generally refers to use of one or more fuel cell stacks in fluid communication. Individual fuel cell elements (plates or cylinders) can typically be “stacked” together in a rectangular array called a “fuel cell stack”. This fuel cell stack can typically take a feed stream and distribute reactants among all of the individual fuel cell elements and can then collect the products from each of these elements. When viewed as a unit, the fuel cell stack in operation can be taken as a whole even though composed of many (often tens or hundreds) of individual fuel cell elements. These individual fuel cell elements can typically have similar voltages (as the reactant and product concentrations are similar), and the total power output can result from the summation of all of the electrical currents in all of the cell elements, when the elements are electrically connected in series. Stacks can also be arranged in a series arrangement to produce high voltages. A parallel arrangement can boost the current. If a sufficiently large volume fuel cell stack is available to process a given flow, the systems and methods described herein can be used with a single solid oxide fuel cell stack. In other aspects of the invention, a plurality of fuel cell stacks may be desirable or needed for a variety of reasons.

[0074] For the purposes of this invention, unless otherwise specified, the term “fuel cell” should be understood to also refer to and/or is defined as including a reference to a fuel cell stack composed of set of one or more individual fuel cell elements for which there is a single input and output, as that is the manner in which fuel cells are typically employed in practice. Similarly, the term fuel cells (plural), unless otherwise specified, should be understood to also refer to and/or is defined as including a plurality of separate fuel cell stacks. In other words, all references within this document, unless specifically noted, can refer interchangeably to the operation of a fuel cell stack as a “fuel cell”. For example, the volume of exhaust generated by a commercial scale combustion generator may be too large for processing by a fuel cell (*e.g.*, a single stack) of conventional size. In order to process the full exhaust, a plurality of fuel cells (*i.e.*, two or more separate fuel cells or fuel cell stacks) can be arranged in parallel, so that each fuel cell can process (roughly) an equal portion of the combustion exhaust. Although multiple fuel cells can be used, each fuel cell can typically be operated in a generally similar manner, given its (roughly) equal portion of the combustion exhaust.

[0075] “Internal reforming” and “external reforming”: A fuel cell or fuel cell stack may include one or more internal reforming sections. As used herein, the term “internal reforming” refers to fuel reforming occurring within the body of a fuel cell, a fuel cell stack, or otherwise within a fuel cell assembly. External reforming, which is often used in conjunction with a fuel cell, occurs in a separate piece of equipment that is located outside of the fuel cell stack. In other words, the body of the external reformer is not in direct physical contact with the body of a fuel cell or fuel cell stack. In a typical set up, the output from the external reformer can be fed to the anode inlet of a fuel cell. Unless otherwise noted specifically, the reforming described within this application is internal reforming.

[0076] Internal reforming may occur within a fuel cell anode. Internal reforming can additionally or alternately occur within an internal reforming element integrated within a fuel cell assembly. The integrated reforming element may be located between fuel cell elements within a fuel cell stack. In other words, one of the trays in the stack can be a reforming section instead of a fuel cell element. In one aspect, the flow arrangement within a fuel cell stack directs fuel to the internal reforming elements and then into the anode portion of the fuel cells. Thus, from a flow perspective, the internal reforming elements and fuel cell elements can be arranged in series within the fuel cell stack. As used herein, the term “anode reforming” is fuel reforming that occurs within an anode. As used herein, the term “internal reforming” is reforming that occurs within an integrated reforming element and not in an anode section.

[0077] In some aspects, a reforming stage that is internal to a fuel cell assembly can be considered to be associated with the anode(s) in the fuel cell assembly. In some alternative aspects, for a reforming stage in a fuel cell stack that can be associated with an anode (such as associated with multiple anodes), a flow path can be available so that the output flow from the reforming stage is passed into at least one anode. This can correspond to having an initial section of a fuel cell plate that is not in contact with the electrolyte and instead serves just as a reforming catalyst. Another option for an associated reforming stage can be to have a separate integrated reforming stage as one of the elements in a fuel cell stack, where the output from the integrated reforming stage is returned to the input side of one or more of the fuel cells in the fuel cell stack.

[0078] From a heat integration standpoint, a characteristic height in a fuel cell stack can be the height of an individual fuel cell stack element. It is noted that the separate reforming stage or a separate endothermic reaction stage could have a different height in the stack than a fuel cell. In such a scenario, the height of a fuel cell element can be used as the characteristic height. In some aspects, an integrated endothermic reaction stage can be defined as a stage that is heat integrated with one or more fuel cells, so that the integrated endothermic reaction stage can use the heat from the fuel cells as a heat source for reforming. Such an integrated endothermic reaction stage can be defined as being positioned less than 5 times the height of a stack element from any fuel cells providing heat to the integrated stage. For example, an integrated endothermic reaction stage (such as a reforming stage) can be positioned less than 5 times the height of a stack element from any fuel cells that are heat integrated, such as less than 3 times the height of a stack element. In this discussion, an integrated reforming stage or integrated endothermic reaction stage that represents an adjacent stack element to a fuel cell element can be defined as being about one stack element height or less away from the adjacent fuel cell element.

[0079] In some aspects, a separate reforming stage that is heat integrated with a fuel cell element can also correspond to a reforming stage that is associated with the fuel cell element. In such aspects, an integrated fuel cell element can provide at least a portion of the heat to the associated reforming stage, and the associated reforming stage can provide at least a portion of the reforming stage output to the integrated fuel cell as a fuel stream. In other aspects, a separate reforming stage can be integrated with a fuel cell for heat transfer without being associated with the fuel cell. In this type of situation, the separate reforming stage can receive heat from the fuel cell, but the output of the reforming stage is not used as an input to the fuel cell. Instead, the output of such a reforming stage can be used for another purpose, such as directly adding the output to the anode exhaust stream, or for forming a separate output stream from the fuel cell assembly.

[0080] More generally, a separate stack element in a fuel cell stack can be used to perform any convenient type of endothermic reaction that can take advantage of the waste heat provided by integrated fuel cell stack elements. Instead of plates suitable for performing a reforming reaction on a hydrocarbon fuel stream, a separate stack element

can have plates suitable for catalyzing another type of endothermic reaction. A manifold or other arrangement of inlet conduits in the fuel cell stack can be used to provide an appropriate input flow to each stack element. A similar manifold or other arrangement of outlet conduits can also be used to withdraw the output flows from each stack element. Optionally, the output flows from an endothermic reaction stage in a stack can be withdrawn from the fuel cell stack without having the output flow pass through a fuel cell anode. In such an optional aspect, the products of the exothermic reaction will therefore exit from the fuel cell stack without passing through a fuel cell anode. Examples of other types of endothermic reactions that can be performed in stack elements in a fuel cell stack include ethanol dehydration to form ethylene and ethane cracking.

[0081] Recycle: As defined herein, recycle of a portion of a fuel cell output (such as an anode exhaust or a stream separated or withdrawn from an anode exhaust) to a fuel cell inlet can correspond to a direct or indirect recycle stream. A direct recycle of a stream to a fuel cell inlet is defined as recycle of the stream without passing through an intermediate process, while an indirect recycle involves recycle after passing a stream through one or more intermediate processes. For example, if the anode exhaust is passed through a CO₂ separation stage prior to recycle, this is considered an indirect recycle of the anode exhaust. If a portion of the anode exhaust, such as an H₂ stream withdrawn from the anode exhaust, is passed into a gasifier for converting coal into a fuel suitable for introduction into the fuel cell, then that is also considered an indirect recycle.

Anode Inputs and Outputs

[0082] In various aspects of the invention, the SOFC array can be fed by a fuel received at the anode inlet that comprises, for example, both hydrogen and a hydrocarbon such as methane (or alternatively a hydrocarbonaceous or hydrocarbon-like compound that may contain heteroatoms different from C and H). Most of the methane (or other hydrocarbonaceous or hydrocarbon-like compound) fed to the anode can typically be fresh methane. In this description, a fresh fuel such as fresh methane refers to a fuel that is not recycled from another fuel cell process. For example, methane recycled from the anode outlet stream back to the anode inlet may not be considered “fresh” methane, and can instead be described as reclaimed methane. The

fuel source used can be shared with other components, such as a turbine. The fuel source input can include water in a proportion to the fuel appropriate for reforming the hydrocarbon (or hydrocarbon-like) compound in the reforming section that generates hydrogen. For example, if methane is the fuel input for reforming to generate H_2 , the molar ratio of water to fuel can be from about one to one to about ten to one, such as at least about two to one. A ratio of four to one or greater is typical for external reforming, but lower values can be typical for internal reforming. To the degree that H_2 is a portion of the fuel source, in some optional aspects no additional water may be needed in the fuel, as the oxidation of H_2 at the anode can tend to produce H_2O that can be used for reforming the fuel. The fuel source can also optionally contain components incidental to the fuel source (*e.g.*, a natural gas feed can contain some content of CO_2 as an additional component). For example, a natural gas feed can contain CO_2 , N_2 , and/or other inert (noble) gases as additional components. Optionally, in some aspects the fuel source may also contain CO, such as CO from a recycled portion of the anode exhaust. An additional or alternate potential source for CO in the fuel into a fuel cell assembly can be CO generated by steam reforming of a hydrocarbon fuel performed on the fuel prior to entering the fuel cell assembly.

[0083] More generally, a variety of types of fuel streams may be suitable for use as an input stream for the anode of a solid oxide fuel cell. Some fuel streams can correspond to streams containing hydrocarbons and/or hydrocarbon-like compounds that may also include heteroatoms different from C and H. In this discussion, unless otherwise specified, a reference to a fuel stream containing hydrocarbons for an SOFC anode is defined to include fuel streams containing such hydrocarbon-like compounds. Examples of hydrocarbon (including hydrocarbon-like) fuel streams include natural gas, streams containing C1 – C4 carbon compounds (such as methane or ethane), and streams containing heavier C5+ hydrocarbons (including hydrocarbon-like compounds), as well as combinations thereof. Still other additional or alternate examples of potential fuel streams for use in an anode input can include biogas-type streams, such as methane produced from natural (biological) decomposition of organic material.

[0084] In some aspects, a solid oxide fuel cell can be used to process an input fuel stream, such as a natural gas and/or hydrocarbon stream, with a low energy content due

to the presence of diluent compounds. For example, some sources of methane and/or natural gas are sources that can include substantial amounts of either CO₂ or other inert molecules, such as nitrogen, argon, or helium. Due to the presence of elevated amounts of CO₂ and/or inerts, the energy content of a fuel stream based on the source can be reduced. Using a low energy content fuel for a combustion reaction (such as for powering a combustion-powered turbine) can pose difficulties. However, a solid oxide fuel cell can generate power based on a low energy content fuel source with a reduced or minimal impact on the efficiency of the fuel cell. The presence of additional gas volume can require additional heat for raising the temperature of the fuel to the temperature for reforming and/or the anode reaction. Additionally, due to the equilibrium nature of the water gas shift reaction within a fuel cell anode, the presence of additional CO₂ can have an impact on the relative amounts of H₂ and CO present in the anode output. However, the inert compounds otherwise can have only a minimal direct impact on the reforming and anode reactions. The amount of CO₂ and/or inert compounds in a fuel stream for a solid oxide fuel cell, when present, can be at least about 1 vol%, such as at least about 2 vol%, or at least about 5 vol%, or at least about 10 vol%, or at least about 15 vol%, or at least about 20 vol%, or at least about 25 vol%, or at least about 30 vol%, or at least about 35 vol%, or at least about 40 vol%, or at least about 45 vol%, or at least about 50 vol %, or at least about 75 vol%. Additionally or alternately, the amount of CO₂ and/or inert compounds in a fuel stream for a solid oxide fuel cell can be about 90 vol% or less, such as about 75 vol% or less, or about 60 vol% or less, or about 50 vol% or less, or about 40 vol% or less, or about 35 vol% or less.

[0085] Yet other examples of potential sources for an anode input stream can correspond to refinery and/or other industrial process output streams. For example, coking is a common process in many refineries for converting heavier compounds to lower boiling ranges. Coking typically produces an off-gas containing a variety of compounds that are gases at room temperature, including CO and various C1 – C4 hydrocarbons. This off-gas can be used as at least a portion of an anode input stream. Other refinery off-gas streams can additionally or alternately be suitable for inclusion in an anode input stream, such as light ends (C1 – C4) generated during cracking or other refinery processes. Still other suitable refinery streams can additionally or alternately

include refinery streams containing CO or CO₂ that also contain H₂ and/or reformable fuel compounds.

[0086] Still other potential sources for an anode input can additionally or alternately include streams with increased water content. For example, an ethanol output stream from an ethanol plant (or another type of fermentation process) can include a substantial portion of H₂O prior to final distillation. Such H₂O can typically cause only minimal impact on the operation of a fuel cell. Thus, a fermentation mixture of alcohol (or other fermentation product) and water can be used as at least a portion of an anode input stream.

[0087] Biogas, or digester gas, is another additional or alternate potential source for an anode input. Biogas may primarily comprise methane and CO₂ and is typically produced by the breakdown or digestion of organic matter. Anaerobic bacteria may be used to digest the organic matter and produce the biogas. Impurities, such as sulfur-containing compounds, may be removed from the biogas prior to use as an anode input.

[0088] The output stream from an SOFC anode can include H₂O, CO₂, CO, and H₂. Optionally, the anode output stream could also have unreacted fuel (such as H₂ or CH₄) or inert compounds in the feed as additional output components. Instead of using this output stream as a fuel source to provide heat for a reforming reaction or as a combustion fuel for heating the cell, one or more separations can be performed on the anode output stream to separate the CO₂ from the components with potential value as inputs to another process, such as H₂ or CO. The H₂ and/or CO can be used as a syngas for chemical synthesis, as a source of hydrogen for chemical reaction, and/or as a fuel with reduced greenhouse gas emissions.

[0089] In various aspects, the composition of the output stream from the anode can be impacted by several factors. Factors that can influence the anode output composition can include the composition of the input stream to the anode, the amount of current generated by the fuel cell, and/or the temperature at the exit of the anode. The temperature of at the anode exit can be relevant due to the equilibrium nature of the water gas shift reaction. In a typical anode, at least one of the plates forming the wall of the anode can be suitable for catalyzing the water gas shift reaction. As a result, if a) the composition of the anode input stream is known, b) the extent of reforming of reformable fuel in the anode input stream is known, and c) the amount of oxygen ions

transported from the cathode to anode (corresponding to the amount of electrical current generated) is known, the composition of the anode output can be determined based on the equilibrium constant for the water gas shift reaction.

$$K_{eq} = [\text{CO}_2] [\text{H}_2] / [\text{CO}] [\text{H}_2\text{O}]$$

[0090] In the above equation, K_{eq} is the equilibrium constant for the reaction at a given temperature and pressure, and $[X]$ is the partial pressure of component X. Based on the water gas shift reaction, it can be noted that an increased CO_2 concentration in the anode input can tend to result in additional CO formation (at the expense of H_2) while an increased H_2O concentration can tend to result in additional H_2 formation (at the expense of CO).

[0091] To determine the composition at the anode output, the composition of the anode input can be used as a starting point. This composition can then be modified to reflect the extent of reforming of any reformable fuels that can occur within the anode. Such reforming can reduce the hydrocarbon content of the anode input in exchange for increased hydrogen and CO_2 . Next, based on the amount of electrical current generated, the amount of H_2 in the anode input can be reduced in exchange for additional H_2O and CO_2 . This composition can then be adjusted based on the equilibrium constant for the water gas shift reaction to determine the exit concentrations for H_2 , CO, CO_2 , and H_2O .

[0092] In various aspects, the operating temperature of the SOFC can be selected to achieve a desired ratio of for H_2 , CO, and CO_2 within a syngas output. The operating temperature may be selected to generate a syngas output with a ratio suitable to be used in an intended process. In an aspect, the operating temperature can range between about 700°C and 1200°C , for example the operating temperature can be about 800°C , about 900°C , about 1000°C , or about 1100°C .

[0093] Optionally, one or more water gas shift reaction stages can be included after the anode output to convert CO and H_2O in the anode output into CO_2 and H_2 , if desired. The amount of H_2 present in the anode output can be increased, for example, by using a water gas shift reactor at lower temperature to convert H_2O and CO present in the anode output into H_2 and CO_2 . As the SOFC can operate at between about 700°C and 1200°C , it may be particularly desirable to facilitate a water gas shift reaction as the anode output is cooled for a use in a subsequent process. Alternatively, the

temperature can be raised and the water-gas shift reaction can be reversed, producing more CO and H₂O from H₂ and CO₂. Water is an expected output of the reaction occurring at the anode, so the anode output can typically have an excess of H₂O relative to the amount of CO present in the anode output. Alternatively, H₂O can be added to the stream after the anode exit but before the water gas shift reaction. CO can be present in the anode output due to incomplete carbon conversion during reforming and/or due to the equilibrium balancing reactions between H₂O, CO, H₂, and CO₂ (*i.e.*, the water-gas shift equilibrium) under either reforming conditions or the conditions present during the anode reaction. A water gas shift reactor can be operated under conditions to drive the equilibrium further in the direction of forming CO₂ and H₂ at the expense of CO and H₂O. Higher temperatures can tend to favor the formation of CO and H₂O. Thus, one option for operating the water gas shift reactor can be to expose the anode output stream to a suitable catalyst, such as a catalyst including iron oxide, zinc oxide, copper on zinc oxide, or the like, at a suitable temperature, *e.g.*, between about 190°C to about 210°C. Optionally, the water-gas shift reactor can include two stages for reducing the CO concentration in an anode output stream, with a first higher temperature stage operated at a temperature from at least about 300°C to about 375°C and a second lower temperature stage operated at a temperature of about 225°C or less, such as from about 180°C to about 210°C. In addition to increasing the amount of H₂ present in the anode output, the water-gas shift reaction can additionally or alternately increase the amount of CO₂ at the expense of CO. This can exchange difficult-to-remove carbon monoxide (CO) for carbon dioxide, which can be more readily removed by condensation (*e.g.*, cryogenic removal), chemical reaction (such as amine removal), and/or other CO₂ removal methods. Additionally or alternately, it may be desirable to increase the CO content present in the anode exhaust in order to achieve a desired ratio of H₂ to CO.

[0094] After passing through the optional water gas shift reaction stage, the anode output can be passed through one or more separation stages for removal of water and/or CO₂ from the anode output stream. For example, one or more CO₂ output streams can be formed by performing CO₂ separation on the anode output using one or more methods individually or in combination. Such methods can be used to generate CO₂ output stream(s) having a CO₂ content of 90 vol% or greater, such as at least 95% vol%

CO₂, or at least 98 vol% CO₂. Such methods can recover about at least about 70% of the CO₂ content of the anode output, such as at least about 80% of the CO₂ content of the anode output, or at least about 90%. Alternatively, in some aspects it may be desirable to recover only a portion of the CO₂ within an anode output stream, with the recovered portion of CO₂ being about 33% to about 90% of the CO₂ in the anode output, such as at least about 40%, or at least about 50%. For example, it may be desirable to retain some CO₂ in the anode output flow so that a desired composition can be achieved in a subsequent water gas shift stage. Suitable separation methods may comprise use of a physical solvent (*e.g.*, Selexol™ or Rectisol™); amines or other bases (*e.g.*, MEA or MDEA); refrigeration (*e.g.*, cryogenic separation); pressure swing adsorption; vacuum swing adsorption; and combinations thereof. A cryogenic CO₂ separator can be an example of a suitable separator. As the anode output is cooled, the majority of the water in the anode output can be separated out as a condensed (liquid) phase. Further cooling and/or pressurizing of the water-depleted anode output flow can then separate high purity CO₂, as the other remaining components in the anode output flow (such as H₂, N₂, CH₄) do not tend to readily form condensed phases. A cryogenic CO₂ separator can recover between about 33% and about 90% of the CO₂ present in a flow, depending on the operating conditions.

[0095] Removal of water from the anode exhaust to form one or more water output streams can also be beneficial, whether prior to, during, or after performing CO₂ separation. The amount of water in the anode output can vary depending on operating conditions selected. For example, the steam-to-carbon ratio established at the anode inlet can affect the water content in the anode exhaust, with high steam-to-carbon ratios typically resulting in a large amount of water that can pass through the anode unreacted and/or reacted only due to the water gas shift equilibrium in the anode. Depending on the aspect, the water content in the anode exhaust can correspond to up to about 30% or more of the volume in the anode exhaust. Additionally or alternately, the water content can be about 80% or less of the volume of the anode exhaust. While such water can be removed by compression and/or cooling with resulting condensation, the removal of this water can require extra compressor power and/or heat exchange surface area and excessive cooling water. One beneficial way to remove a portion of this excess water can be based on use of an adsorbent bed that can capture the humidity from the moist

anode effluent and can then be 'regenerated' using dry anode feed gas, in order to provide additional water for the anode feed. HVAC-style (heating, ventilation, and air conditioning) adsorption wheels design can be applicable, because anode exhaust and inlet can be similar in pressure, and minor leakage from one stream to the other can have minimal impact on the overall process. In embodiments where CO₂ removal is performed using a cryogenic process, removal of water prior to or during CO₂ removal may be desirable, including removal by triethyleneglycol (TEG) system and/or desiccants. By contrast, if an amine wash is used for CO₂ removal, water can be removed from the anode exhaust downstream from the CO₂ removal stage.

[0096] Alternately or in addition to a CO₂ output stream and/or a water output stream, the anode output can be used to form one or more product streams containing a desired chemical or fuel product. Such a product stream or streams can correspond to a syngas stream, a hydrogen stream, or both syngas product and hydrogen product streams. For example, a hydrogen product stream containing at least about 70 vol% H₂, such as at least about 90 vol% H₂ or at least about 95 vol% H₂, can be formed. Additionally or alternately, a syngas stream containing at least about 70 vol% of H₂ and CO combined, such as at least about 90 vol% of H₂ and CO can be formed. The one or more product streams can have a gas volume corresponding to at least about 75% of the combined H₂ and CO gas volumes in the anode output, such as at least about 85% or at least about 90% of the combined H₂ and CO gas volumes. It is noted that the relative amounts of H₂ and CO in the products streams may differ from the H₂ to CO ratio in the anode output based on use of water gas shift reaction stages to convert between the products.

[0097] In some aspects, it can be desirable to remove or separate a portion of the H₂ present in the anode output. For example, in some aspects the H₂ to CO ratio in the anode exhaust can be at least about 3.0 : 1. By contrast, processes that make use of syngas, such as Fischer-Tropsch synthesis, may consume H₂ and CO in a different ratio, such as a ratio that is closer to 2 : 1. One alternative can be to use a water gas shift reaction to modify the content of the anode output to have an H₂ to CO ratio closer to a desired syngas composition. Another alternative can be to use a membrane separation to remove a portion of the H₂ present in the anode output to achieve a desired ratio of H₂ and CO, or still alternately to use a combination of membrane separation and water gas shift reactions. One advantage of using a membrane

separation to remove only a portion of the H_2 in the anode output can be that the desired separation can be performed under relatively mild conditions. Since one goal can be to produce a retentate that still has a substantial H_2 content, a permeate of high purity hydrogen can be generated by membrane separation without requiring severe conditions. For example, rather than having a pressure on the permeate side of the membrane of about 100 kPaa or less (such as ambient pressure), the permeate side can be at an elevated pressure relative to ambient while still having sufficient driving force to perform the membrane separation. Additionally or alternately, a sweep gas such as methane can be used to provide a driving force for the membrane separation. This can reduce the purity of the H_2 permeate stream, but may be advantageous, depending on the desired use for the permeate stream.

[0098] In various aspects of the invention, at least a portion of the anode exhaust stream (preferably after separation of CO_2 and/or H_2O) can be used as a feed for a process external to the fuel cell and associated reforming stages. In various aspects, the anode exhaust can have a ratio of H_2 to CO of about 1.5 : 1 to about 10 : 1, such as at least about 3.0 : 1, or at least about 4.0 : 1, or at least about 5.0 : 1. A syngas stream can be generated or withdrawn from the anode exhaust. The anode exhaust gas, optionally after separation of CO_2 and/or H_2O , and optionally after performing a water gas shift reaction and/or a membrane separation to remove excess hydrogen, can correspond to a stream containing substantial portions of H_2 and/or CO. For a stream with a relatively low content of CO, such as a stream where the ratio of H_2 to CO is at least about 3 : 1, the anode exhaust can be suitable for use as an H_2 feed. Examples of processes that could benefit from an H_2 feed can include, but are not limited to, refinery processes, an ammonia synthesis plant, or a turbine in a (different) power generation system, or combinations thereof. Depending on the application, still lower CO_2 contents can be desirable. For a stream with an H_2 -to-CO ratio of less than about 2.2 to 1 and greater than about 1.9 to 1, the stream can be suitable for use as a syngas feed. Examples of processes that could benefit from a syngas feed can include, but are not limited to, a gas-to-liquids plant (such as a plant using a Fischer-Tropsch process with a non-shifting catalyst) and/or a methanol synthesis plant. The amount of the anode exhaust used as a feed for an external process can be any convenient amount. Optionally, when a portion of the anode exhaust is used as a feed for an external

process, a second portion of the anode exhaust can be recycled to the anode input and/or recycled to the combustion zone for a combustion-powered generator.

[0099] The input streams useful for different types of Fischer-Tropsch synthesis processes can provide an example of the different types of product streams that may be desirable to generate from the anode output. For a Fischer-Tropsch synthesis reaction system that uses a shifting catalyst, such as an iron-based catalyst, the desired input stream to the reaction system can include CO₂ in addition to H₂ and CO. If a sufficient amount of CO₂ is not present in the input stream, a Fischer-Tropsch catalyst with water gas shift activity can consume CO in order to generate additional CO₂, resulting in a syngas that can be deficient in CO. For integration of such a Fischer-Tropsch process with an SOFC fuel cell, the separation stages for the anode output can be operated to retain a desired amount of CO₂ (and optionally H₂O) in the syngas product. By contrast, for a Fischer-Tropsch catalyst based on a non-shifting catalyst, any CO₂ present in a product stream could serve as an inert component in the Fischer-Tropsch reaction system.

[00100] In an aspect where the membrane is swept with a sweep gas such as a methane sweep gas, the methane sweep gas can correspond to a methane stream used as the anode fuel or in a different low pressure process, such as a boiler, furnace, gas turbine, or other fuel-consuming device. In such an aspect, low levels of CO₂ permeation across the membrane can have minimal consequence. Such CO₂ that may permeate across the membrane can have a minimal impact on the reactions within the anode, and such CO₂ can remain contained in the anode product. Therefore, the CO₂ (if any) lost across the membrane due to permeation does not need to be transferred again across the SOFC electrolyte. This can significantly reduce the separation selectivity requirement for the hydrogen permeation membrane. This can allow, for example, use of a higher-permeability membrane having a lower selectivity, which can enable use of a lower pressure and/or reduced membrane surface area. In such an aspect of the invention, the volume of the sweep gas can be a large multiple of the volume of hydrogen in the anode exhaust, which can allow the effective hydrogen concentration on the permeate side to be maintained close to zero. The hydrogen thus separated can be incorporated into the turbine-fed methane where it can enhance the turbine combustion characteristics, as described above.

[00101] It is noted that excess H_2 produced in the anode can represent a fuel where the greenhouse gases have already been separated. Any CO_2 in the anode output can be readily separated from the anode output, such as by using an amine wash, a cryogenic CO_2 separator, and/or a pressure or vacuum swing absorption process. Several of the components of the anode output (H_2 , CO , CH_4) are not easily removed, while CO_2 and H_2O can usually be readily removed. Depending on the embodiment, at least about 90 vol% of the CO_2 in the anode output can be separated out to form a relatively high purity CO_2 output stream. Thus, any CO_2 generated in the anode can be efficiently separated out to form a high purity CO_2 output stream. After separation, the remaining portion of the anode output can correspond primarily to components with chemical and/or fuel value, as well as reduced amounts of CO_2 and/or H_2O . Since a substantial portion of the CO_2 generated by the original fuel (prior to reforming) can have been separated out, the amount of CO_2 generated by subsequent burning of the remaining portion of the anode output can be reduced. In particular, to the degree that the fuel in the remaining portion of the anode output is H_2 , no additional greenhouse gases can typically be formed by burning of this fuel.

[00102] The anode exhaust can be subjected to a variety of gas processing options, including water-gas shift and separation of the components from each other. Two general anode processing schemes are shown in FIGS. 1 and 2.

[00103] FIG. 1 schematically shows an example of a reaction system for operating a fuel cell array of solid oxide fuel cells in conjunction with a chemical synthesis process. In FIG. 1, a fuel stream 105 is provided to a reforming stage (or stages) 110 associated with the anode 127 of a fuel cell 120, such as a fuel cell that is part of a fuel cell stack in a fuel cell array. The reforming stage 110 associated with fuel cell 120 can be internal to a fuel cell assembly. In some optional aspects, an external reforming stage (not shown) can also be used to reform a portion of the reformable fuel in an input stream prior to passing the input stream into a fuel cell assembly. Fuel stream 105 can preferably include a reformable fuel, such as methane, other hydrocarbons, and/or other hydrocarbon-like compounds such as organic compounds containing carbon-hydrogen bonds. Fuel stream 105 can also optionally contain H_2 and/or CO , such as H_2 and/or CO provided by optional anode recycle stream 185. It is noted that anode recycle stream 185 is optional, and that in many aspects no recycle stream is provided from the

anode exhaust 125 back to anode 127, either directly or indirectly via combination with fuel stream 105 or reformed fuel stream 115. After reforming, the reformed fuel stream 115 can be passed into anode 127 of fuel cell 120. An O_2 -containing stream 119 can also be passed into cathode 129. A flow of oxygen ions 122, O_2^{2-} , from the cathode portion 129 of the fuel cell can provide the remaining reactant needed for the anode fuel cell reactions. Based on the reactions in the anode 127, the resulting anode exhaust 125 can include H_2O , one or more components corresponding to incompletely reacted fuel (H_2 , CO , CH_4 , or other components corresponding to a reformable fuel), and optionally one or more additional nonreactive components, such as CO_2 , N_2 and/or other contaminants that are part of fuel stream 105. The anode exhaust 125 can then be passed into one or more separation stages. For example, a CO_2 removal stage 140 can correspond to a cryogenic CO_2 removal system, an amine wash stage for removal of acid gases such as CO_2 , or another suitable type of CO_2 separation stage for separating a CO_2 output stream 143 from the anode exhaust. Optionally, the anode exhaust can first be passed through a water gas shift reactor 130 to convert any CO present in the anode exhaust (along with some H_2O) into CO_2 and H_2 in an optionally water gas shifted anode exhaust 135. Depending on the nature of the CO_2 removal stage, a water condensation or removal stage 150 may be desirable to remove a water output stream 153 from the anode exhaust. Though shown in FIG. 1 after the CO_2 separation stage 140, it may optionally be located before the CO_2 separation stage 140 instead. Additionally, an optional membrane separation stage 160 for separation of H_2 can be used to generate a high purity permeate stream 163 of H_2 . The resulting retentate stream 166 can then be used as an input to a chemical synthesis process. Stream 166 could additionally or alternately be shifted in a second water-gas shift reactor 131 to adjust the H_2 , CO , and CO_2 content to a different ratio, producing an output stream 168 for further use in a chemical synthesis process. In FIG. 1, anode recycle stream 185 is shown as being withdrawn from the retentate stream 166, but the anode recycle stream 185 could additionally or alternately be withdrawn from other convenient locations in or between the various separation stages. The separation stages and shift reactor(s) could additionally or alternately be configured in different orders, and/or in a parallel configuration. Finally, a stream with a reduced content of O_2 139 can be generated as an output from cathode 129. For the sake of simplicity, various stages of compression

and heat addition/removal that might be useful in the process, as well as steam addition or removal, are not shown.

[00104] As noted above, the various types of separations performed on the anode exhaust can be performed in any convenient order. FIG. 2 shows an example of an alternative order for performing separations on an anode exhaust. In FIG. 2, anode exhaust 125 can be initially passed into separation stage 260 for removing a portion 263 of the hydrogen content from the anode exhaust 125. This can allow, for example, reduction of the H₂ content of the anode exhaust to provide a retentate 266 with a ratio of H₂ to CO closer to 2 : 1. The ratio of H₂ to CO can then be further adjusted to achieve a desired value in a water gas shift stage 230. The water gas shifted output 235 can then pass through CO₂ separation stage 240 and water removal stage 250 to produce an output stream 275 suitable for use as an input to a desired chemical synthesis process. Optionally, output stream 275 could be exposed to an additional water gas shift stage (not shown). A portion of output stream 275 can optionally be recycled (not shown) to the anode input. Of course, still other combinations and sequencing of separation stages can be used to generate a stream based on the anode output that has a desired composition. For the sake of simplicity, various stages of compression and heat addition/removal that might be useful in the process, as well as steam addition or removal, are not shown.

Cathode Inputs and Outputs

[00105] Conventionally, a solid oxide fuel cell can be operated based on drawing a desired load while consuming some portion of the fuel in the fuel stream delivered to the anode. The voltage of the fuel cell can then be determined by the load, fuel input to the anode, air and O₂ provided to the cathode, and the internal resistances of the fuel cell. By removing any direct link between the composition of the anode input flow and the cathode input flow, additional options become available for operating the fuel cell, such as to generate excess synthesis gas and/or to improve the total efficiency (electrical plus chemical power) of the fuel cell, among others.

[00106] The amount of O₂ present in a cathode input stream can advantageously be sufficient to provide the oxygen needed for the cathode reaction in the fuel cell. Thus, the volume percentage of O₂ can advantageously be at least 0.5 times the amount of O₂ in the cathode exhaust. Optionally, as necessary, additional air can be added to the

cathode input to provide sufficient oxidant for the cathode reaction. When some form of air is used as the oxidant, the amount of N_2 in the cathode exhaust can be at least about 78 vol%, *e.g.*, at least about 88 vol%, and/or about 95 vol% or less. In some aspects, the cathode input stream can additionally or alternately contain compounds that are generally viewed as contaminants, such as H_2S or NH_3 . In other aspects, the cathode input stream can be cleaned to reduce or minimize the content of such contaminants.

[00107] The conditions in the cathode can additionally or alternately be suitable for conversion of unburned hydrocarbons (in combination with O_2 in the cathode input stream) to typical combustion products, such as CO_2 and H_2O .

Fuel Cell Arrangement

[00108] In various aspects, a fuel cell array can be operated to improve or maximize the energy output of the fuel cell, such as the total energy output, the electric energy output, the syngas chemical energy output, or a combination thereof. For example, solid oxide fuel cells can be operated with an excess of reformable fuel in a variety of situations, such as for generation of a syngas stream for use in chemical synthesis plant and/or for generation of a high purity hydrogen stream. The syngas stream and/or hydrogen stream can be used as a syngas source, a hydrogen source, as a clean fuel source, and/or for any other convenient application. In such aspects, the amount of O_2 in the cathode exhaust can be related to the amount of O_2 in the cathode input stream and the O_2 utilization at the desired operating conditions for improving or maximizing the fuel cell energy output.

Solid oxide Fuel Cell Operation

[00109] In an aspect, the operating temperature of the SOFC can range between about 700C and 1200C, for example the operating temperature can be about 800C, about 900C, about 1000C, or about 1100C. In an aspect, the operating temperature may be selected to push the WGS reaction within the anode to a desired ratio.

[00110] In some aspects, a fuel cell may be operated in a single pass or once-through mode. In single pass mode, reformed products in the anode exhaust are not returned to the anode inlet. Thus, recycling syngas, hydrogen, or some other product from the anode output directly to the anode inlet is not done in single pass operation. More generally, in single pass operation, reformed products in the anode exhaust are also not

returned indirectly to the anode inlet, such as by using reformed products to process a fuel stream subsequently introduced into the anode inlet. Heat from the anode exhaust or output may additionally or alternately be recycled in a single pass mode. For example, the anode output flow may pass through a heat exchanger that cools the anode output and warms another stream, such as an input stream for the anode and/or the cathode. Recycling heat from anode to the fuel cell is consistent with use in single pass or once-through operation. Optionally but not preferably, constituents of the anode output may be burned to provide heat to the fuel cell during single pass mode.

[00111] FIG. 3 shows a schematic example of the operation of an SOFC for generation of electrical power. In FIG. 3, the anode portion of the fuel cell can receive fuel and steam (H_2O) as inputs, with outputs of water, and optionally excess H_2 , CH_4 (or other hydrocarbons), and/or CO . The cathode portion of the fuel cell can receive O_2 (e.g., air) as inputs, with an output corresponding to O_2 -depleted oxidant (air). Within the fuel cell, O_2^{2-} ions formed in the cathode side can be transported across the electrolyte to provide the oxygen ions needed for the reactions occurring at the anode.

[00112] Several reactions can occur within a solid oxide fuel cell such as the example fuel cell shown in FIG. 3. The reforming reactions can be optional, and can be reduced or eliminated if sufficient H_2 is provided directly to the anode. The following reactions are based on CH_4 , but similar reactions can occur when other fuels are used in the fuel cell.

- (1) <anode reforming> $\text{CH}_4 + \text{H}_2\text{O} \Rightarrow 3\text{H}_2 + \text{CO}$
- (2) <water gas shift> $\text{CO} + \text{H}_2\text{O} \Rightarrow \text{H}_2 + \text{CO}_2$
- (3) <reforming and water gas shift combined> $\text{CH}_4 + 2\text{H}_2\text{O} \Rightarrow 4\text{H}_2 + \text{CO}_2$
- (4) <anode H_2 oxidation> $\text{H}_2 + \text{O}_2^{2-} \Rightarrow \text{H}_2\text{O} + 2\text{e}^-$
- (5) <cathode> $\frac{1}{2}\text{O}_2 + 2\text{e}^- \Rightarrow \text{O}_2^{2-}$

[00113] Reaction (1) represents the basic hydrocarbon reforming reaction to generate H_2 for use in the anode of the fuel cell. The CO formed in reaction (1) can be converted to H_2 by the water-gas shift reaction (2). The combination of reactions (1) and (2) is shown as reaction (3). Reactions (1) and (2) can occur external to the fuel cell, and/or the reforming can be performed internal to the anode.

[00114] Reactions (4) and (5), at the anode and cathode respectively, represent the reactions that can result in electrical power generation within the fuel cell. Reaction (4)

combines H₂, either present in the feed or optionally generated by reactions (1) and/or (2), with oxygen ions to form H₂O and electrons to the circuit. Reaction (5) combines O₂ and electrons from the circuit to form oxygen ions. The oxygen ions generated by reaction (5) can be transported across the electrolyte of the fuel cell to provide the oxygen ions needed for reaction (4). In combination with the transport of oxygen ions across the electrolyte, a closed current loop can then be formed by providing an electrical connection between the anode and cathode.

[00115] In various embodiments, a goal of operating the fuel cell can be to improve the total efficiency of the fuel cell and/or the total efficiency of the fuel cell plus an integrated chemical synthesis process. This is typically in contrast to conventional operation of a fuel cell, where the goal can be to operate the fuel cell with high electrical efficiency for using the fuel provided to the cell for generation of electrical power. As defined above, total fuel cell efficiency may be determined by dividing the electric output of the fuel cell plus the lower heating value of the fuel cell outputs by the lower heating value of the input components for the fuel cell. In other words, $TFCE = (LHV(el) + LHV(sg\ out))/LHV(in)$, where LHV(in) and LHV(sg out) refer to the LHV of the fuel components (such as H₂, CH₄, and/or CO) delivered to the fuel cell and syngas (H₂, CO and/or CO₂) in the anode outlet streams or flows, respectively. This can provide a measure of the electric energy plus chemical energy generated by the fuel cell and/or the integrated chemical process. It is noted that under this definition of total efficiency, heat energy used within the fuel cell and/or used within the integrated fuel cell / chemical synthesis system can contribute to total efficiency. However, any excess heat exchanged or otherwise withdrawn from the fuel cell or integrated fuel cell / chemical synthesis system is excluded from the definition. Thus, if excess heat from the fuel cell is used, for example, to generate steam for electricity generation by a steam turbine, such excess heat is excluded from the definition of total efficiency.

[00116] Several operational parameters may be manipulated to operate a fuel cell with excess reformable fuel. Some parameters can be similar to those currently recommended for fuel cell operation. In some aspects, the cathode conditions and temperature inputs to the fuel cell can be similar to those recommended in the literature. For example, the desired electrical efficiency and the desired total fuel cell efficiency may be achieved at a range of fuel cell operating temperatures typical for

solid oxide fuel cells. In typical operation, the temperature can increase across the fuel cell.

[00117] In other aspects, the operational parameters of the fuel cell can deviate from typical conditions so that the fuel cell is operated to allow a temperature decrease from the anode inlet to the anode outlet and/or from the cathode inlet to the cathode outlet. For example, the reforming reaction to convert a hydrocarbon into H_2 and CO is an endothermic reaction. If a sufficient amount of reforming is performed in a fuel cell anode relative to the amount of oxidation of hydrogen to generate electrical current, the net heat balance in the fuel cell can be endothermic. This can cause a temperature drop between the inlets and outlets of a fuel cell. During endothermic operation, the temperature drop in the fuel cell can be controlled so that the electrolyte in the fuel cell remains in a molten state.

[00118] Parameters that can be manipulated in a way so as to differ from those currently recommended can include the amount of fuel provided to the anode, the composition of the fuel provided to the anode, and/or the separation and capture of syngas in the anode output without significant recycling of syngas from the anode exhaust to either the anode input or the cathode input. In some aspects, no recycle of syngas or hydrogen from the anode exhaust to either the anode input or the cathode input can be allowed to occur, either directly or indirectly. In additional or alternative aspects, a limited amount of recycle can occur. In such aspects, the amount of recycle from the anode exhaust to the anode input and/or the cathode input can be less than about 10 vol% of the anode exhaust, such as less than about 5 vol%, or less than about 1 vol%.

[00119] In some embodiments, the fuel cells in a fuel cell array can be arranged so that only a single stage of fuel cells (such as fuel cell stacks) can be present. In this type of embodiment, the anode fuel utilization for the single stage can represent the anode fuel utilization for the array. Another option can be that a fuel cell array can contain multiple stages of anodes and multiple stages of cathodes, with each anode stage having a fuel utilization within the same range, such as each anode stage having a fuel utilization within 10% of a specified value, for example within 5% of a specified value. Still another option can be that each anode stage can have a fuel utilization equal to a specified value or lower than the specified value by less than an amount, such as having

each anode stage be not greater than a specified value by 10% or less, for example, by 5% or less. As an illustrative example, a fuel cell array with a plurality of anode stages can have each anode stage be within about 10% of 50% fuel utilization, which would correspond to each anode stage having a fuel utilization between about 40% and about 60%. As another example, a fuel cell array with a plurality of stages can have each anode stage be not greater than 60% anode fuel utilization with the maximum deviation being about 5% less, which would correspond to each anode stage having a fuel utilization between about 55% to about 60%. In still another example, one or more stages of fuel cells in a fuel cell array can be operated at a fuel utilization from about 30% to about 50%, such as operating a plurality of fuel cell stages in the array at a fuel utilization from about 30% to about 50%. More generally, any of the above types of ranges can be paired with any of the anode fuel utilization values specified herein.

[00120] Yet still another additional or alternate option can be to specify an overall average of fuel utilization over all fuel cells in a fuel cell array. In various aspects, the overall average of fuel utilization for a fuel cell array can be about 65% or less, for example, about 60% or less, about 55% or less, about 50% or less, or about 45% or less (additionally or alternately, the overall average fuel utilization for a fuel cell array can be at least about 25%, for example at least about 30%, at least about 35%, or at least about 40%). Such an average fuel utilization need not necessarily constrain the fuel utilization in any single stage, so long as the array of fuel cells meets the desired fuel utilization.

Applications for Syngas Output after Capture

[00121] The components from an anode output stream and/or cathode output stream can be used for a variety of purposes. One option can be to use the anode output as a source of hydrogen, as described above. For an SOFC integrated with or co-located with a refinery, the hydrogen can be used as a hydrogen source for various refinery processes, such as hydroprocessing. Such hydrogen can be used in a refinery or other industrial setting as a fuel for a boiler, furnace, and/or fired heater, and/or the hydrogen can be used as a feed for an electric power generator, such as a turbine. Hydrogen from an SOFC fuel cell can further additionally or alternately be used as an input stream for other types of fuel cells that require hydrogen as an input, possibly including vehicles

powered by fuel cells. Still another option can be to additionally or alternately use syngas generated as an output from an SOFC fuel cell as a fermentation input.

[00122] Another option can be to additionally or alternately use syngas generated from the anode output. Of course, syngas can be used as a fuel, although a syngas based fuel can still lead to some CO₂ production when burned as fuel. In other aspects, a syngas output stream can be used as an input for a chemical synthesis process. One option can be to additionally or alternately use syngas for a Fischer-Tropsch type process, and/or another process where larger hydrocarbon molecules are formed from the syngas input. Another option can be to additionally or alternately use syngas to form an intermediate product such as methanol. Methanol could be used as the final product, but in other aspects methanol generated from syngas can be used to generate larger compounds, such as gasoline, olefins, aromatics, and/or other products. It is noted that a small amount of CO₂ can be acceptable in the syngas feed to a methanol synthesis process, and/or to a Fischer-Tropsch process utilizing a shifting catalyst. Hydroformylation is an additional or alternate example of still another synthesis process that can make use of a syngas input.

[00123] It is noted that one variation on use of an SOFC to generate syngas can be to use SOFC fuel cells as part of a system for processing methane and/or natural gas withdrawn by an offshore oil platform or other production system that is a considerable distance from its ultimate market. Instead of attempting to transport the gas phase output from a well, or attempting to store the gas phase product for an extended period, the gas phase output from a well can be used as the input to an SOFC fuel cell array. This can lead to a variety of benefits. First, the electric power generated by the fuel cell array can be used as a power source for the platform. Additionally, the syngas output from the fuel cell array can be used as an input for a Fischer-Tropsch process at the production site. This can allow for formation of liquid hydrocarbon products more easily transported by pipeline, ship, or railcar from the production site to, for example, an on-shore facility or a larger terminal.

[00124] Still other integration options can additionally or alternately include using the cathode output as a source of higher purity, heated nitrogen. The cathode input can often include a large portion of air, which means a substantial portion of nitrogen can be included in the cathode input. The fuel cell can transport O₂ from the cathode across

the electrolyte to the anode, and the cathode outlet can have lower concentrations of O₂, and thus a higher concentration of N₂ than found in air. With subsequent removal of the residual O₂, this nitrogen output can be used as an input for production of ammonia or other nitrogen-containing chemicals, such as urea, ammonium nitrate, and/or nitric acid. It is noted that urea synthesis could additionally or alternately use CO₂ separate from the anode output as an input feed.

Additional Embodiments

[00125] Embodiment 1. A method for producing electricity, and hydrogen or syngas, using a solid oxide fuel cell having an anode and cathode, the method comprising: introducing a fuel stream comprising a reformable fuel into the anode of the solid oxide fuel cell, a reforming stage (comprising an internal reforming element) associated with the anode of the solid oxide fuel cell, or a combination thereof; introducing a cathode inlet stream comprising O₂ into the cathode of the solid oxide fuel cell; generating electricity within the solid oxide fuel cell; and withdrawing, from an anode exhaust, a gas stream comprising H₂, a gas stream comprising H₂ and CO, or a combination thereof, wherein an electrical efficiency for the solid oxide fuel cell is between about 10% and about 50% and a total fuel cell productivity for the solid oxide fuel cell is at least about 150 mW/cm².

[00126] Embodiment 2. The method of Embodiment 1, wherein the solid oxide fuel cell is operated to generate electricity at a thermal ratio of about 0.25 to about 1.3, or about 1.15 or less, or about 1.0 or less, or about 0.75 or less.

[00127] Embodiment 3. The method of any of the above embodiments, wherein a reformable fuel surplus ratio of the fuel stream comprising the reformable fuel is at least about 2.0, or at least about 2.5.

[00128] Embodiment 4. The method of any of the above embodiments, wherein the electrical efficiency of the solid oxide fuel cell is about 45% or less, or about 35% or less.

[00129] Embodiment 5. The method of any of the above embodiments, wherein a total fuel cell efficiency for the solid oxide fuel cell is at least about 65%, or at least about 70%, or at least about 75%, or at least about 80%.

[00130] Embodiment 6. The method of any of the above embodiments, wherein the total fuel cell productivity for the solid oxide fuel cell is at least about 150 mW/cm², or

at least about 300 mW/cm², or at least about 350 mW/cm², or about 800 mW/cm² or less.

[00131] Embodiment 7. The method of any of the above embodiments, wherein a total reformable fuel productivity for the solid oxide fuel cell is at least about 75 mW/cm², or at least about 100 mW/cm², or at least about 150 mW/cm², or at least about 200 mW/cm², or about 600 mW/cm² or less.

[00132] Embodiment 8. The method of any of the above embodiments, wherein a reformable hydrogen content of reformable fuel introduced into the anode of the solid oxide fuel cell, a reforming stage (comprising an internal reforming element) associated with the anode of the solid oxide fuel cell, or a combination thereof is at least about 75% greater than the amount of hydrogen reacted to generate electricity, such as at least about 100% greater.

[00133] Embodiment 9. The method of any of the above embodiments, wherein the fuel stream comprises at least about 10 vol% inert compounds, at least about 10 vol% CO₂, or a combination thereof.

[00134] Embodiment 10. The method of any of the above embodiments, wherein the fuel cell is operated at a voltage V_A of about 0.67 Volts or less, or about 0.5 Volts or less.

[00135] Embodiment 11. The method of any of the above embodiments, wherein the anode exhaust has a ratio of H₂ to CO of about 1.5:1 to about 10:1.

[00136] Embodiment 12. The method of any of the above embodiments, wherein the anode exhaust has a ratio of H₂ to CO of at least about 3.0:1.

[00137] Embodiment 13. The method of any of the above embodiments, wherein the solid oxide fuel cell is a tubular solid oxide fuel cell.

[00138] Embodiment 14. The method of any of the above embodiments, wherein the solid oxide fuel cell further comprises one or more integrated endothermic reaction stages.

[00139] Embodiment 15. The method of Embodiment 14, wherein at least one integrated endothermic reaction stage comprises an integrated reforming stage, the fuel stream introduced into the anode of the solid oxide fuel cell being passed through the integrated reforming stage prior to entering the anode of the solid oxide fuel cell.

[00140] Embodiment 16. The method of any of Embodiments 1-15, wherein a temperature at the anode outlet is greater than a temperature at the anode inlet by about 40°C or less.

[00141] Embodiment 17. The method of any of Embodiments 1-15, wherein a temperature at the anode inlet differs from a temperature at the anode outlet by about 20°C or less.

[00142] Embodiment 18. The method of any of Embodiments 1-15, wherein a temperature at the anode outlet is less than a temperature at the anode inlet by about 10°C to about 80°C.

[00143] Embodiment 19. The method of any of Embodiments 1-15, wherein a thermal ratio is about 0.85 or less, the method further comprising supplying heat to the fuel cell to maintain a temperature at the anode outlet that is less than the temperature at the anode inlet by about 5°C to about 50°C.

[00144] Embodiment 20. The method of any of the above embodiments, the method further comprising reforming the reformable fuel, wherein at least about 90% of the reformable fuel introduced into the anode of the solid oxide fuel cell, a reforming stage (comprising an internal reforming element) associated with the anode of the solid oxide fuel cell, or a combination thereof is reformed in a single pass through the anode of the solid oxide fuel cell.

[00145] Although the present invention has been described in terms of specific embodiments, it is not so limited. Suitable alterations/modifications for operation under specific conditions should be apparent to those skilled in the art. It is therefore intended that the following claims be interpreted as covering all such alterations/modifications that fall within the true spirit/scope of the invention.

CLAIMS:

What is claimed is:

1. A method for producing electricity, and hydrogen or syngas, using a solid oxide fuel cell having an anode and cathode, the method comprising:
 - introducing a fuel stream comprising a reformable fuel into the anode of the solid oxide fuel cell, a reforming stage (comprising an internal reforming element) associated with the anode of the solid oxide fuel cell, or a combination thereof;
 - introducing a cathode inlet stream comprising O₂ into the cathode of the solid oxide fuel cell;
 - generating electricity within the solid oxide fuel cell; and
 - withdrawing, from an anode exhaust, a gas stream comprising H₂, a gas stream comprising H₂ and CO, or a combination thereof,wherein an electrical efficiency for the solid oxide fuel cell is between about 10% and about 50% and a total fuel cell productivity for the solid oxide fuel cell is at least about 150 mW/cm².
2. The method of claim 1, wherein the solid oxide fuel cell is operated to generate electricity at a thermal ratio of about 0.25 to about 1.3, for example about 1.15 or less, about 1.0 or less, or about 0.75 or less.
3. The method of any of the above claims, wherein a reformable fuel surplus ratio of the fuel stream comprising the reformable fuel is at least about 2.0, for example at least about 2.5.
4. The method of any of the above claims, wherein the electrical efficiency of the solid oxide fuel cell is about 45% or less, for example about 35% or less.
5. The method of any of the above claims, wherein a total fuel cell efficiency for the solid oxide fuel cell is at least about 65%, for example at least about 70%, at least about 75%, or at least about 80%.
6. The method of any of the above claims, wherein the total fuel cell productivity for the solid oxide fuel cell is at least about 150 mW/cm², for example at least about 300 mW/cm², at least about 350 mW/cm², or about 800 mW/cm² or less.
7. The method of any of the above claims, wherein a total reformable fuel productivity for the solid oxide fuel cell is at least about 75 mW/cm², for example at

least about 100 mW/cm^2 , at least about 150 mW/cm^2 , at least about 200 mW/cm^2 , or about 600 mW/cm^2 or less.

8. The method of any of the above claims, wherein a reformable hydrogen content of reformable fuel introduced into the anode of the solid oxide fuel cell, a reforming stage (comprising an internal reforming element) associated with the anode of the solid oxide fuel cell, or a combination thereof, is at least about 75% greater than the amount of hydrogen reacted to generate electricity, such as at least about 100% greater.

9. The method of any of the above claims, wherein the fuel stream comprises at least about 10 vol% inert compounds, at least about 10 vol% CO_2 , or a combination thereof.

10. The method of any of the above claims, wherein the fuel cell is operated at a voltage V_A of about 0.67 Volts or less, for example about 0.5 Volts or less.

11. The method of any of the above claims, wherein the anode exhaust has a ratio of H_2 to CO of about 1.5:1 to about 10:1, for example at least about 3.0:1.

12. The method of any of the above claims, wherein the solid oxide fuel cell is a tubular solid oxide fuel cell.

13. The method of any of the above claims, wherein the solid oxide fuel cell further comprises one or more integrated endothermic reaction stages.

14. The method of claim 13, wherein at least one integrated endothermic reaction stage comprises an integrated reforming stage, the fuel stream introduced into the anode of the solid oxide fuel cell being passed through the integrated reforming stage prior to entering the anode of the solid oxide fuel cell.

15. The method of any of claims 1-14, wherein a temperature at the anode outlet is greater than a temperature at the anode inlet by about 40°C or less.

16. The method of any of claims 1-14, wherein a temperature at the anode inlet differs from a temperature at the anode outlet by about 20°C or less.

17. The method of any of claims 1-14, wherein a temperature at the anode outlet is less than a temperature at the anode inlet by about 10°C to about 80°C .

18. The method of any of claims 1-14, wherein a thermal ratio is about 0.85 or less, the method further comprising supplying heat to the fuel cell to maintain a temperature at the anode outlet that is less than the temperature at the anode inlet by about 5°C to about 50°C .

19. The method of any of the above claims, the method further comprising reforming the reformable fuel, wherein at least about 90% of the reformable fuel introduced into the anode of the solid oxide fuel cell, a reforming stage (comprising an internal reforming element) associated with the anode of the solid oxide fuel cell, or a combination thereof, is reformed in a single pass through the anode of the solid oxide fuel cell.

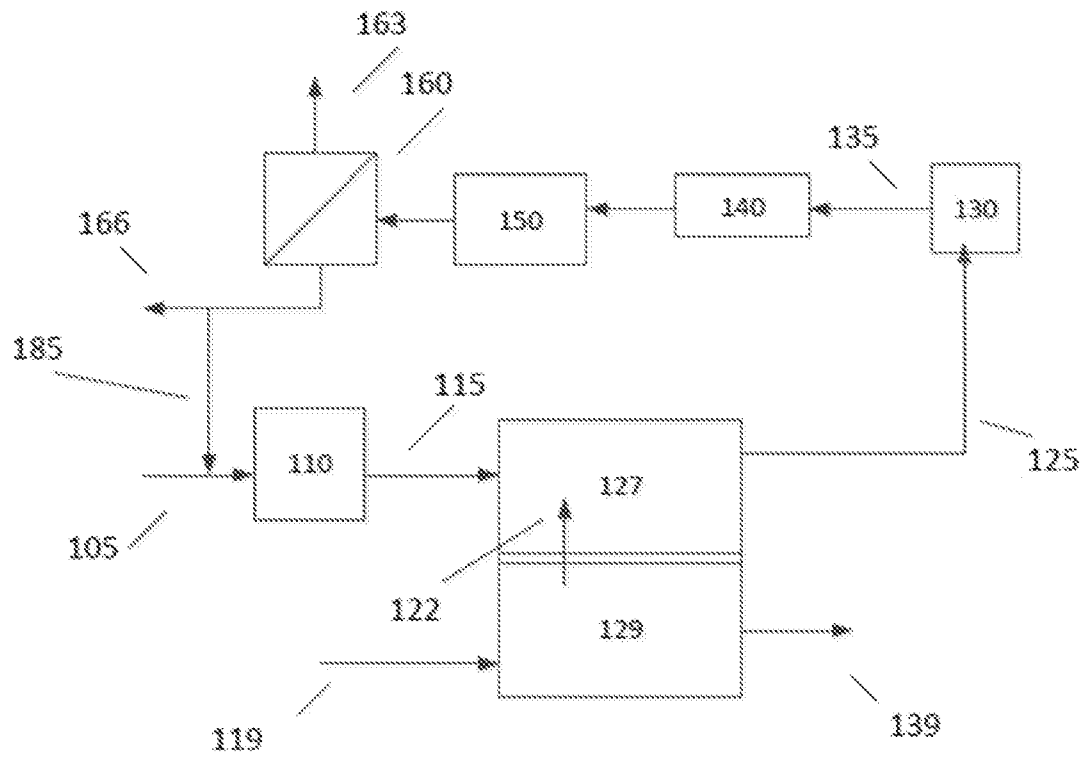


FIG. 1

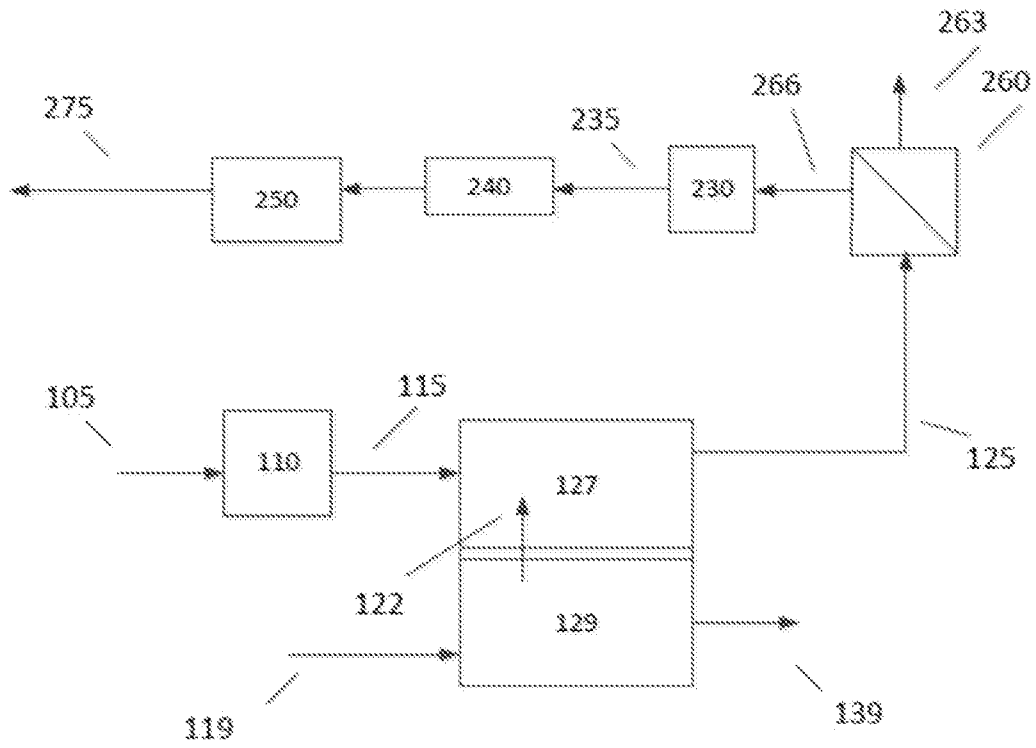


FIG. 2

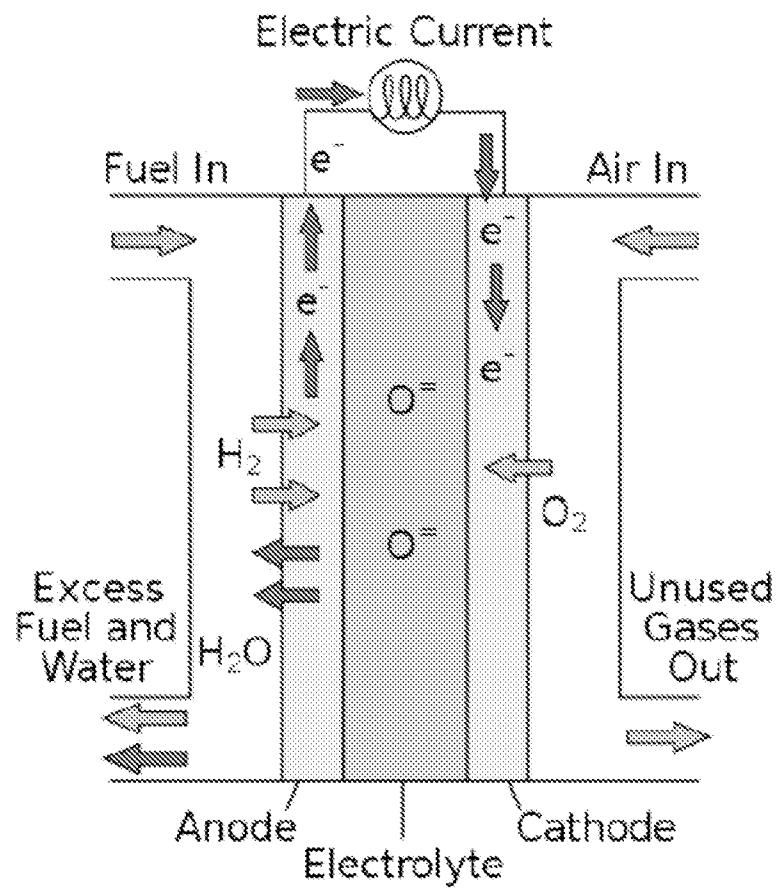


FIG. 3

INTERNATIONAL SEARCH REPORT

International application No
PCT/US2014/058015

A. CLASSIFICATION OF SUBJECT MATTER

INV. H01M8/24 H01M8/04 H01M8/14 C01B3/38 H01M8/06
H01M8/10

ADD.

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 F01K F02C C01B

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 practicable, search terms used)

EP0-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	US 6 162 556 A (VOLLMAR HORST [DE] ET AL) 19 December 2000 (2000-12-19) column 2, line 29 - column 2, line 65 column 3, line 13 - line 26 column 3, line 44 - line 50 column 5, line 35 - column 6, line 57 figure 1	1-19
X	US 2004/202914 A1 (SRIDHAR K R [US] ET AL) 14 October 2004 (2004-10-14) the whole document	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 application or patent but published on or after the international filing date

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"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

"&" document member of the same patent family

Date of the actual completion of the international search

18 December 2014

Date of mailing of the international search report

07/01/2015

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INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

PCT/US2014/058015

Patent document cited in search report		Publication date	Patent family member(s)	Publication date
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US 2004202914	A1	14-10-2004	EP 1620906 A2	01-02-2006
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			US 2008318092 A1	25-12-2008
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