

STOICHIOMETRIC COMBUSTION OF ENRICHED AIR WITH EXHAUST GAS RECIRCULATION

CROSS-REFERENCE TO RELATED APPLICATIONS

5 [0001] This application claims the benefit of U. S. provisional patent application number 61/361,178, filed July 2, 2010 entitled "Stoichiometric Combustion of Enriched Air With Exhaust Gas Recirculation", the entirety of which is incorporated by reference herein.

[0002] This application contains subject matter related to U.S. Patent Application Number 61/361,169, filed July 2, 2010 entitled "Systems and Methods for Controlling
10 Combustion of a Fuel"; U. S. Patent Application Number 61/361,170, filed July 2, 2010 entitled "Low Emission Triple-Cycle Power Generation Systems and Methods"; U.S. Patent Application Number 61/361,173, filed July 2, 2010, entitled "Low Emission Triple-Cycle Power Generation Systems and Methods"; U.S. Patent Application Number 61/361,176, filed July 2, 2010, entitled "Stoichiometric Combustion With Exhaust Gas Recirculation and
15 Direct Contact Cooler"; U.S. Patent Application Number 61/361,180 filed July 2, 2010, entitled "Low Emission Power Generation Systems and Methods".

FIELD

[0003] Embodiments of the disclosure relate to low emission power generation in combined-cycle power systems. More particularly, embodiments of the disclosure relate to
20 methods and apparatus for combusting a fuel for enhanced carbon dioxide (CO₂) manufacture and capture.

BACKGROUND

[0004] This section is intended to introduce various aspects of the art, which may be associated with exemplary embodiments of the present disclosure. This discussion is
25 believed to assist in providing a framework to facilitate a better understanding of particular aspects of the present disclosure. Accordingly, it should be understood that this section should be read in this light, and not necessarily as admissions of prior art.

[0005] With the growing concern on global climate change and the impact of CO₂ emissions, emphasis has been placed on CO₂ capture from power plants. This concern
30 combined with the implementation of cap-and-trade policies in many countries make reducing CO₂ emissions a priority for these and other countries as well as the companies that operate hydrocarbon production systems therein.

[0006] Gas turbine combined-cycle power plants are rather efficient and can be operated at relatively low cost when compared to other technologies, such as coal and nuclear. Capturing CO₂ from the exhaust of gas turbine combined-cycle plants, however, can be difficult for several reasons. For instance, there is typically a low concentration of CO₂ in the exhaust compared to the large volume of gas that must be treated. Also, additional cooling is often required before introducing the exhaust to a CO₂ capture system and the exhaust can become saturated with water after cooling, thereby increasing the reboiler duty in the CO₂ capture system. Other common factors can include the low pressure and large quantities of oxygen frequently contained in the exhaust. All of these factors result in a high cost of CO₂ capture from gas turbine combined-cycle power plants.

[0007] At least one approach to lowering CO₂ emissions in combined-cycle systems includes stoichiometric combustion and exhaust gas recirculation. In a conventional exhaust gas recirculation system, such as a natural gas combined cycle (NGCC), a recycled component of the exhaust gas is mixed with ambient air and introduced into the compressor section of a gas turbine. Typical CO₂ concentrations in the exhaust of a NGCC are around 3% – 4%, but can increase above 4% with exhaust recirculation. In operation, conventional NGCC systems require only about 40% of the air intake volume to provide adequate stoichiometric combustion of the fuel, while the remaining 60% of the air volume serves as a diluent to moderate the temperature and cool the exhaust to a temperature suitable for introduction into the succeeding expander. Recirculating a portion of the exhaust gas increases the CO₂ concentration in the exhaust, which can subsequently be used as the diluent in the combustion system.

[0008] However, due to the molecular weight, specific heat, Mach number effects, etc. of CO₂, without significant modifications to either the compressor or the expander sections, standard gas turbines are limited as to the concentration of CO₂ that can be tolerated in the compression section of the gas turbine from the exhaust. For example, the limit on CO₂ content in the exhaust recirculated to the compression section of a standard gas turbine is about 20wt% CO₂.

[0009] Moreover, the typical NGCC system produces low pressure exhaust which requires a fraction of the power produced via expansion of the exhaust in order to extract the CO₂ for sequestration or enhanced oil recovery (EOR), thereby reducing the thermal efficiency of the NGCC. Further, the equipment for the CO₂ extraction is large and expensive, and several stages of compression are required to take the ambient pressure gas to the pressure required for EOR or sequestration. Such limitations are typical of post-

combustion carbon capture from low pressure exhaust associated with the combustion of other fossil fuels, such as coal.

[0010] The foregoing discussion of need in the art is intended to be representative rather than exhaustive. A technology addressing one or more such needs, or some other related
5 shortcoming in the field, would benefit power generation in combined-cycle power systems.

SUMMARY

[0011] The present disclosure is directed to integrated systems and methods for improving power generation systems. In some implementations, the present disclosure provides a gas turbine system, comprising a first compressor, a second compressor, a
10 combustion chamber, and an expander. The first compressor may be configured to receive and compress a recycled exhaust gas into a compressed recycle exhaust gas. The second compressor may be configured to receive and compress enriched air to generate a compressed oxidant. The combustion chamber may be configured to receive the compressed recycle exhaust gas and the compressed oxidant and to stoichiometrically combust a fuel stream. The
15 compressed recycle exhaust gas serves as a diluent to moderate combustion temperatures. The expander may be configured to receive a discharge from the combustion chamber to generate the recycled exhaust gas. The expander further may be coupled to the first compressor to drive, at least partially, the first compressor.

[0012] Additionally or alternatively, the present disclosure provides methods of
20 generating power. Exemplary methods include: a) compressing a recycled exhaust gas in a main compressor to generate a compressed recycle exhaust gas; b) compressing enriched air in an inlet compressor to generate a compressed oxidant; c) stoichiometrically combusting the compressed oxidant and a fuel in a combustion chamber and in the presence of the compressed recycle exhaust gas, thereby generating a discharge stream, wherein the
25 compressed recycle exhaust gas acts as a diluent configured to moderate the temperature of the discharge stream; and d) expanding the discharge stream in an expander to at least partially drive the main compressor and generate the recycled exhaust gas and at least partially drive the main compressor.

[0013] Still additionally or alternatively, the present disclosure provides integrated power
30 generation systems. Exemplary integrated power generation systems include both a gas turbine system and an exhaust gas recirculation system. The gas turbine system may comprise a first compressor, a second compressor, a combustion chamber, and an expander. The first compressor may be configured to receive and compress a recycled exhaust gas into

a compressed recycle exhaust gas. The second compressor may be configured to receive and compress enriched air to generate a compressed oxidant, the enriched air having an oxygen concentration between about 30wt% and about 50wt%. The combustion chamber may be configured to receive the compressed recycle exhaust gas and the compressed oxidant and to stoichiometrically combust a fuel stream, wherein the compressed recycle exhaust gas serves as a diluent to moderate combustion temperatures. The expander may be configured to receive a discharge from the combustion chamber to generate the recycled exhaust stream. The expander further may be coupled to the first compressor and adapted to drive, at least partially, the first compressor. The exhaust gas recirculation system may include a heat recovery steam generator, one or more cooling units, and a boost compressor. The heat recovery steam generator may be communicably coupled to a steam gas turbine. The heat recovery steam generator may be being configured to receive the exhaust gas from the expander to create steam that generates electrical power in the steam generator. The one or more cooling units may be configured to cool the recycled exhaust gas received from the heat recovery steam generator and to remove condensed water from the recycled exhaust gas. The boost compressor may be configured to increase the pressure of the recycled exhaust gas before injection into the first compressor to provide the compressed recycle exhaust gas.

BRIEF DESCRIPTION OF THE DRAWINGS

[0014] The foregoing and other advantages of the present disclosure may become apparent upon reviewing the following detailed description and drawings of non-limiting examples of embodiments in which:

[0015] FIG. 1 depicts a schematic of an integrated system for low emission power generation and enhanced CO₂ recovery, according to one or more embodiments described.

[0016] FIG. 2 depicts another schematic of an integrated system for low emission power generation and enhanced CO₂ recovery, according to one or more embodiments described.

[0017] FIG. 3 depicts another schematic of an integrated system for low emission power generation and enhanced CO₂ recovery, according to one or more embodiments described.

DETAILED DESCRIPTION

[0018] In the following detailed description section, the specific embodiments of the present disclosure are described in connection with preferred embodiments. However, to the extent that the following description is specific to a particular embodiment or a particular use of the present disclosure, this is intended to be for exemplary purposes only and simply provides a description of the exemplary embodiments. Accordingly, the disclosure is not

limited to the specific embodiments described below, but rather, it includes all alternatives, modifications, and equivalents falling within the true spirit and scope of the appended claims.

[0019] Various terms as used herein are defined below. To the extent a term used in a claim is not defined below, it should be given the broadest definition persons in the pertinent art have given that term as reflected in at least one printed publication or issued patent.

[0020] As used herein, the term "natural gas" refers to a multi-component gas obtained from a crude oil well (associated gas) or from a subterranean gas-bearing formation (non-associated gas). The composition and pressure of natural gas can vary significantly. A typical natural gas stream contains methane (CH_4) as a major component, *i.e.* greater than 50 mol% of the natural gas stream is methane. The natural gas stream can also contain ethane (C_2H_6), higher molecular weight hydrocarbons (*e.g.*, C_3 - C_{20} hydrocarbons), one or more acid gases (*e.g.*, hydrogen sulfide, carbon dioxide), or any combination thereof. The natural gas can also contain minor amounts of contaminants such as water, nitrogen, iron sulfide, wax, crude oil, or any combination thereof.

[0021] As used herein, the term "stoichiometric combustion" refers to a combustion reaction having a volume of reactants comprising a fuel and an oxidizer and a volume of products formed by combusting the reactants where the entire volume of the reactants is used to form the products. As used herein, the term "substantially stoichiometric combustion" refers to a combustion reaction having a molar ratio of combustion fuel to oxygen ranging from about plus or minus 10% of the oxygen required for a stoichiometric ratio or more preferably from about plus or minus 5% of the oxygen required for the stoichiometric ratio. For example, the stoichiometric ratio of fuel to oxygen for methane is 1:2 ($\text{CH}_4 + 2\text{O}_2 \rightarrow \text{CO}_2 + 2\text{H}_2\text{O}$). Propane will have a stoichiometric ratio of fuel to oxygen of 1:5. Another way of measuring substantially stoichiometric combustion is as a ratio of oxygen supplied to oxygen required for stoichiometric combustion, such as from about 0.9:1 to about 1.1:1, or more preferably from about 0.95:1 to about 1.05:1.

[0022] As used herein, the term "stream" refers to a volume of fluids, although use of the term stream typically means a moving volume of fluids (*e.g.*, having a velocity or mass flow rate). The term "stream," however, does not require a velocity, mass flow rate, or a particular type of conduit for enclosing the stream.

[0023] Embodiments of the presently disclosed systems and processes can be used to produce ultra low emission electric power and CO_2 for enhanced oil recovery (EOR) and/or sequestration applications. In one or more embodiments, a mixture of enriched air and fuel

can be stoichiometrically or substantially stoichiometrically combusted and simultaneously mixed with a stream of recycled exhaust gas. The stream of recycled exhaust gas, generally including products of combustion such as CO₂, can be used as a diluent to control, adjust, or otherwise moderate the temperature of combustion and the exhaust that enters the succeeding expander. As a result of using enriched air, the recycled exhaust gas can have an increased CO₂ content, thereby allowing the expander to operate at even higher expansion ratios for the same inlet and discharge temperatures, thereby producing significantly increased power.

[0024] Combustion in commercial gas turbines at stoichiometric conditions or substantially stoichiometric conditions (*e.g.*, "slightly rich" combustion) can prove advantageous in order to eliminate the cost of excess oxygen removal. By cooling the exhaust and condensing the water out of the cooled exhaust stream, a relatively high content CO₂ exhaust stream can be produced. While a portion of the recycled exhaust gas can be utilized for temperature moderation in the closed Brayton cycle, a remaining purge stream can be used for EOR applications and/or electric power can be produced with little or no sulfur oxides (SO_x), nitrogen oxides (NO_x), and/or CO₂ being emitted to the atmosphere. The result of this process is the production of power in three separate cycles and the manufacturing of additional CO₂.

[0025] Referring now to the figures, FIG. 1 depicts a schematic of an illustrative integrated system **100** for power generation and CO₂ recovery using a combined-cycle arrangement, according to one or more embodiments. In at least one embodiment, the power generation system **100** can include a gas turbine system **102** characterized as a power-producing, closed Brayton cycle. The gas turbine system **102** can have a first or main compressor **104** coupled to an expander **106** via a shaft **108**. The shaft **108** can be any mechanical, electrical, or other power coupling, thereby allowing a portion of the mechanical energy generated by the expander **106** to drive the main compressor **104**. In at least one embodiment, the gas turbine system **102** can be a standard gas turbine, where the main compressor **104** and expander **106** form the compressor and expander ends, respectively. In other embodiments, however, the main compressor **104** and expander **106** can be individualized components in the system **102**.

[0026] The gas turbine system **102** can also include a combustion chamber **110** configured to combust a fuel introduced via line **112** and mixed with an oxidant introduced via line **114**. In one or more embodiments, the fuel in line **112** can include any suitable hydrocarbon gas or liquid, such as natural gas, methane, ethane, naphtha, butane, propane, syngas, diesel, kerosene, aviation fuel, coal derived fuel, bio-fuel, oxygenated hydrocarbon

feedstock, or any combinations thereof. The oxidant via line **114** can be derived from a second or inlet compressor **118** fluidly coupled to the combustion chamber **110** and adapted to compress a feed oxidant introduced via line **120**. In one or more embodiments, the feed oxidant in line **120** can include atmospheric air, enriched air, or combinations thereof. When
5 the oxidant in line **114** includes a mixture of atmospheric air and enriched air, the enriched air can be compressed by the inlet compressor **118** either before or after being mixed with the atmospheric air. The enriched air can have an overall oxygen concentration of about 30wt%, about 35wt%, about 40wt%, about 45wt%, or about 50wt%.

[0027] The enriched air can be derived from several sources, including implementing
10 various technologies upstream of the inlet compressor **118** to produce the enriched air. For example, the enriched air can be derived from such separation technologies as membrane separation, pressure swing adsorption, temperature swing adsorption, nitrogen plant-by-product streams, and/or combinations thereof. The enriched air can also be derived from an air separation unit (ASU), such as a cryogenic ASU, for producing nitrogen for pressure
15 maintenance or other purposes. The reject stream from the ASU can be rich in oxygen, having an overall oxygen content of about 50wt% to about 70wt%. This reject stream can be used as at least a portion of the enriched air and subsequently diluted, if needed, with unprocessed atmospheric air to obtain the desired oxygen concentration for the application.

[0028] As will be described in more detail below, the combustion chamber **110** can also
20 receive a compressed recycle exhaust gas in line **144**, including an exhaust gas recirculation primarily having CO₂ and nitrogen components. The compressed recycle exhaust gas in line **144** can be derived from the main compressor **104** and adapted to help facilitate a stoichiometric or substantially stoichiometric combustion of the compressed oxidant in line **114** and fuel in line **112** by moderating the temperature of the combustion products. As can
25 be appreciated, recirculating the exhaust gas can serve to increase the CO₂ concentration in the exhaust gas.

[0029] An exhaust gas in line **116** directed to the inlet of the expander **106** can be generated as a product of combustion of the fuel in line **112** and the compressed oxidant in line **114**, in the presence of the compressed recycle exhaust gas in line **144**. In at least one
30 embodiment, the fuel in line **112** can be primarily natural gas, thereby generating a discharge or exhaust gas via line **116** that can include volumetric portions of vaporized water, CO₂, nitrogen, nitrogen oxides (NO_x), and sulfur oxides (SO_x). In some embodiments, a small portion of unburned fuel in line **112** or other compounds can also be present in the exhaust gas in line **116** due to combustion equilibrium limitations. As the exhaust gas in line **116**

expands through the expander **106** it generates mechanical power to drive the main compressor **104**, an electrical generator, or other facilities, and also produces a gaseous exhaust in line **122** having a heightened CO₂ content resulting from the influx of the compressed recycle exhaust gas in line **144**. In some implementations the expander **106** may be adapted to produce additional mechanical power that may be used for other purposes.

[0030] The power generation system **100** can also include an exhaust gas recirculation (EGR) system **124**. In one or more embodiments, the EGR system **124** can include a heat recovery steam generator (HRSG) **126**, or similar device, fluidly coupled to a steam gas turbine **128**. In at least one embodiment, the combination of the HRSG **126** and the steam gas turbine **128** can be characterized as a power-producing closed Rankine cycle. In combination with the gas turbine system **102**, the HRSG **126** and the steam gas turbine **128** can form part of a combined-cycle power generating plant, such as a natural gas combined-cycle (NGCC) plant. The gaseous exhaust in line **122** can be introduced to the HRSG **126** in order to generate steam via line **130** and a cooled exhaust gas in line **132**. In one embodiment, the steam in line **130** can be sent to the steam gas turbine **128** to generate additional electrical power.

[0031] The cooled exhaust gas in line **132** can be sent to a first cooling unit **134** adapted to cool the cooled exhaust gas in line **132** and generate a cooled recycle gas stream **140**. The first cooling unit **134** can include, for example, one or more contact coolers, trim coolers, evaporative cooling unit, or any combination thereof. The first cooling unit **134** can also be adapted to remove a portion of any condensed water from the cooled exhaust gas in line **132** via a water dropout stream **138**. In at least one embodiment, the water dropout stream **138** may be routed to the HRSG **126** via line **141** to provide a water source for the generation of additional steam in line **130** therein. In other embodiments, the water recovered via the water dropout stream **138** can be used for other downstream applications, such as supplementary heat exchanging processes.

[0032] In one or more embodiments, the cooled recycle gas stream **140** can be directed to a boost compressor **142**. Cooling the cooled exhaust gas in line **132** in the first cooling unit **134** can reduce the power required to compress the cooled recycle gas stream **140** in the boost compressor **142**. As opposed to a conventional fan or blower system, the boost compressor **142** can be configured to compress and increase the overall density of the cooled recycle gas stream **140**, thereby directing a pressurized recycle gas in line **145** downstream, where the pressurized recycle gas in line **145** has an increased mass flow rate for the same volumetric flow. This can prove advantageous since the main compressor **104** can be volume-flow

limited, and directing more mass flow through the main compressor **104** can result in higher discharge pressures, thereby translating into higher pressure ratios across the expander **106**. Higher pressure ratios generated across the expander **106** can allow for higher inlet temperatures and, therefore, an increase in expander **106** power and efficiency. As can be appreciated, this may prove advantageous since the CO₂-rich exhaust gas in line **116** generally maintains a higher specific heat capacity.

[0033] Since the suction pressure of the main compressor **104** is a function of its suction temperature, a cooler suction temperature will demand less power to operate the main compressor **104** for the same mass flow. Consequently, the pressurized recycle gas in line **145** can optionally be directed to a second cooling unit **136**. The second cooling unit **136** can include, for example, one or more direct contact coolers, trim coolers, evaporative cooling units, or any combination thereof. In at least one embodiment, the second cooling unit **136** can serve as an aftercooler adapted to remove at least a portion of the heat of compression generated by the boost compressor **142** on the pressurized recycle gas in line **145**. The second cooling unit **136** can also extract additional condensed water via a water dropout stream **143**. In one or more embodiments, the water dropout streams **138**, **143** can converge into stream **141** and may or may not be routed to the HRSG **126** to generate additional steam via line **130** therein.

[0034] While only first and second cooling units **134**, **136** are depicted herein, it will be appreciated that any number of cooling units can be employed to suit a variety of applications, without departing from the scope of the disclosure. In fact, contemplated herein are embodiments where the cooled exhaust gas in line **132** is further directed to an evaporative cooling unit associated with the exhaust gas recirculation loop, such as generally described in the concurrently filed U.S. Patent Application entitled "Stoichiometric Combustion with Exhaust Gas Recirculation and Direct Contact Cooler," the contents of which are hereby incorporated by reference to the extent not inconsistent with the present disclosure. As described therein, the exhaust gas recirculation system may include any variety of equipment adapted to provide the exhaust gas to the main compressor for injection into the combustion chamber.

[0035] The main compressor **104** can be configured to receive and compress the pressurized recycle gas in line **145** to a pressure nominally at or above the pressure of the combustion chamber **110**, thereby generating the compressed recycle exhaust gas in line **144**. As can be appreciated, cooling the pressurized recycle gas in line **145** in the second cooling unit **136** after compression in the boost compressor **142** can allow for an increased volumetric

mass flow of exhaust gas into the main compressor **104**. Consequently, this can reduce the amount of power required to compress the pressurized recycle gas in line **145** to a predetermined pressure.

[0036] In at least one embodiment, a purge stream **146** can be recovered from the compressed recycle exhaust gas in line **144** and subsequently treated in a CO₂ separator **148** to capture CO₂ at an elevated pressure via line **150**. The separated CO₂ in line **150** can be used for sales, used in another processes requiring CO₂, and/or further compressed and injected into a terrestrial reservoir for enhanced oil recovery (EOR), sequestration, or another purpose. Because of the stoichiometric or substantially stoichiometric combustion of the fuel in line **112** combined with a boosted pressure from the boost compressor **142**, the CO₂ partial pressure in the purge stream **146** can be much higher than in conventional gas turbine exhausts. As a result, carbon capture in the CO₂ separator **148** can be undertaken using low-energy separation processes, such as employing less energy-intensive solvents. At least one suitable solvent is potassium carbonate (K₂CO₃) which absorbs SO_x and/or NO_x, and converts them to useful compounds, such as potassium sulfite (K₂SO₃), potassium nitrate (KNO₃), and other simple fertilizers. Exemplary systems and methods of using potassium carbonate for CO₂ capture can be found in the concurrently filed U.S. Patent Application entitled "Low Emission Triple-Cycle Power Generation Systems and Methods," the contents of which are hereby incorporated by reference to the extent not inconsistent with the present disclosure.

[0037] A residual stream **151**, essentially depleted of CO₂ and consisting primarily of nitrogen, can also be derived from the CO₂ separator **148**. In one or more embodiments, the residual stream **151** can be introduced to a gas expander **152** to provide power and an expanded depressurized gas, or exhaust gas, via line **156**. The expander **152** can be, for example, a power-producing nitrogen expander. As depicted, the gas expander **152** can be optionally coupled to the inlet compressor **118** through a common shaft **154** or other mechanical, electrical, or other power coupling, thereby allowing a portion of the power generated by the gas expander **152** to drive the inlet compressor **118**. However, during start-up of the system **100** and/or during normal operation when the gas expander **152** is unable to supply all the required power to operate the inlet compressor **118**, at least one motor **158**, such as an electric motor, can be used synergistically with the gas expander **152**. For instance, the motor **158** can be sensibly sized such that during normal operation of the system **100**, the motor **158** can be configured to supply the power short-fall from the gas expander **152**. In other embodiments, however, the gas expander **152** can be used to provide power to

other applications, and not directly coupled to the inlet compressor **118**. For example, there may be a substantial mismatch between the power generated by the expander **152** and the requirements of the compressor **118**. In such cases, the expander **152** could be adapted to drive a smaller (or larger) compressor (not shown) that demands less (or more) power.

5 [0038] An expanded depressurized gas in line **156**, primarily consisting of dry nitrogen gas, can be discharged from the gas expander **152**. In at least one embodiment, the combination of the gas expander **152**, inlet compressor **118**, and CO₂ separator **148** can be characterized as an open Brayton cycle, or a third power-producing component of the power generation system **100**. Illustrative systems and methods of expanding the nitrogen gas in the
10 residual stream **151**, and variations thereof, can be found in the concurrently filed U.S. Patent Application entitled "Low Emission Triple-Cycle Power Generation Systems and Methods," the contents of which are hereby incorporated by reference to the extent not inconsistent with the present disclosure.

[0039] Referring now to FIG. 2, depicted is another schematic of an illustrative integrated
15 system **200** for power generation and CO₂ recovery using a combined-cycle arrangement, according to one or more embodiments. The system **200** of FIG. 2 is substantially similar to the system **100** of FIG. 1 and therefore will not be discussed in detail where like elements correspond to like numerals. The system **200** of FIG. 2, however, can replace the gas expander **152** of system **100** with a downstream compressor **158** configured to compress the
20 residual stream **151** and generate a compressed exhaust gas via line **160**. In one or more embodiments, the compressed exhaust gas in line **160** can be suitable for injection into a reservoir for pressure maintenance applications. In applications where methane gas is typically reinjected into hydrocarbon wells to maintain well pressures, compressing the residual stream **151** may prove advantageous. For example, the pressurized nitrogen gas in
25 line **160** can instead be injected into the hydrocarbon wells and any residual methane gas can be sold or otherwise used as a fuel in related applications, such as providing fuel in line **112**.

[0040] Referring to FIG. 3, depicted is another schematic of an illustrative integrated system **300** for power generation and CO₂ recovery using a combined-cycle arrangement, according to one or more embodiments. The system **300** of FIG. 3 is substantially similar to
30 the systems **100** and **200** of FIGs. 1 and 2, respectively, and therefore will not be discussed in detail where like elements correspond to like numerals. As depicted, the system **300** can be characterized as a hybrid arrangement of the power-producing nitrogen gas expander **152** as discussed with reference to FIG. 1, and the pressure maintenance downstream compressor **158** as discussed with reference to FIG. 2. In one or more embodiments, the residual stream

151 can be split, thereby directing a first portion of the residual stream **151** to the gas expander **152**, and at the same time directing a second portion of the residual stream **151** to the downstream compressor **158** via line **162**. In at least one embodiment, the respective volumetric mass flow of the first and second portions can be manipulated so as to provide
5 predetermined and/or desired amounts of the residual stream **151** to either location to maximize production.

[0041] By using enriched air as the compressed oxidant in line **114** and pressurizing the exhaust gas in the boost compressor **142**, the power generation system **100** can achieve higher concentrations of CO₂ in the exhaust gas, thereby allowing for more effective CO₂
10 separation and capture. Embodiments disclosed herein can effectively increase the concentration of CO₂ in the exhaust gas in line **116** to CO₂ concentrations ranging from about 10wt% to about 20wt%. To achieve such CO₂ concentrations, the combustion chamber **110** can be adapted to stoichiometrically or substantially stoichiometrically combust an incoming mixture of fuel in line **112** and compressed oxidant in line **114**, where the compressed oxidant
15 in line **114** includes enriched air having an overall oxygen concentration of about 30wt%, about 35wt%, about 40wt%, about 45wt%, or about 50wt%.

[0042] In order to moderate the temperature of the stoichiometric combustion and meet expander **106** inlet temperature and component cooling requirements, a portion of the exhaust gas with increased CO₂ content derived from the compressed recycle exhaust gas in line **144**
20 can be injected into the combustion chamber **110** as a diluent. Thus, embodiments of the disclosure can essentially eliminate excess oxygen from the exhaust gas in line **116** while also increasing its CO₂ concentration to about 20wt%. As such, the gaseous exhaust in line **122** can have less than about 3.0wt% oxygen, or less than about 1.0wt% oxygen, or less than about 0.1wt% oxygen, or even less than about 0.001wt% oxygen.

[0043] At least one benefit of having an increased CO₂ concentration is that the expander **106** can be operated at an even higher expansion ratio for the same inlet and discharge temperatures, and thereby produce increased power. This is due to the higher heat capacity of CO₂ relative to nitrogen found in ambient air. In one or more embodiments, the expansion ratio of the expander **106** can be increased from about 17.0 to about 20.0 corresponding to
30 about 10wt% and about 20wt% CO₂ recycle streams, respectively. Embodiments using enriched air having about 35wt% oxygen can be used in order to achieve the about 20wt% in the CO₂ recycle stream.

[0044] Other benefits of having an increased CO₂ concentration in the recycle gas include an increased concentration of CO₂ in the extracted purge stream **146** used for CO₂ separation.

Because of its increased CO₂ concentration, the purge stream **146** need not be as large in order to extract the required amounts of CO₂. For example, the equipment handling extraction for CO₂ separation can be smaller, including its piping, heat exchangers, valves, absorber towers, etc. Moreover, increased concentrations of CO₂ can improve the performance of CO₂ removal technology, including using low-energy separation processes, such as employing less energy-intensive solvents that would otherwise be untenable. Consequently, capital expenditures for capturing CO₂ can be dramatically lowered.

[0045] The specifics of exemplary operation of the system **100** will now be discussed. As will be appreciated, specific temperatures and pressures achieved or experienced in the various components of any of the embodiments disclosed herein can change depending on, among other factors, the purity of the oxidant used and/or the specific makes and/or models of expanders, compressors, coolers, etc. Accordingly, it will be appreciated that the particular data described herein is for illustrative purposes only and should not be construed as the only interpretation thereof. In an embodiment, the inlet compressor **118** can provide compressed oxidant in line **114** at pressures ranging between about 280 psia and about 300 psia. Also contemplated herein, however, is aeroderivative gas turbine technology, which can produce and consume pressures of up to about 750 psia and more.

[0046] The main compressor **104** can be configured to recycle and compress recycled exhaust gas into the compressed recycle exhaust gas in line **144** at a pressure nominally above or at the combustion chamber **110** pressure, and use a portion of that recycled exhaust gas as a diluent in the combustion chamber **110**. Because amounts of diluent needed in the combustion chamber **110** can depend on the purity of the oxidant used for stoichiometric combustion or the particular model or design of expander **106**, a ring of thermocouples and/or oxygen sensors (not shown) can be disposed on the outlet of the expander **106**. In operation, the thermocouples and sensors can be adapted to regulate and determine the volume of exhaust gas required as diluent needed to cool the products of combustion to the required expander inlet temperature, and also regulate the amount of oxidant being injected into the combustion chamber **110**. Thus, in response to the heat requirements detected by the thermocouples and the oxygen levels detected by the oxygen sensors, the volumetric mass flow of compressed recycle exhaust gas in line **144** and compressed oxidant in line **114** can be manipulated or fluctuate to match the demand. Illustrative embodiments and more detailed descriptions of systems and methods for controlling the composition of an exhaust gas produced by combusting a fuel can be found in the concurrently filed U.S. Patent Application entitled "Systems and Methods for Controlling Combustion of a Fuel," the

contents of which are hereby incorporated by reference to the extent not inconsistent with the present disclosure.

[0047] In at least one embodiment, a pressure drop of about 12-13 psia can be experienced across the combustion chamber **110** during stoichiometric or substantially stoichiometric combustion. Combustion of the fuel in line **112** and the compressed oxidant in line **114** can generate temperatures between about 2000 °F and about 3000 °F and pressures ranging from 250 psia to about 300 psia. As described above, because of the increased mass flow and higher specific heat capacity of the CO₂-rich exhaust gas derived from the compressed recycle exhaust gas in line **144**, higher pressure ratios can be achieved across the expander **106**, thereby allowing for higher inlet temperatures and increased expander **106** power.

[0048] The gaseous exhaust in line **122** exiting the expander **106** can exhibit pressures at or near ambient. In at least one embodiment, the gaseous exhaust in line **122** can have a pressure of about 13-17 psia. The temperature of the gaseous exhaust in line **122** can be about 1225 °F to about 1275 °F before passing through the HRSG **126** to generate steam in line **130** and a cooled exhaust gas in line **132**. In one or more embodiments, the cooling unit **134** can reduce the temperature of the cooled exhaust gas in line **132** thereby generating the cooled recycle gas stream **140** having a temperature between about 32 °F and about 120 °F. As can be appreciated, such temperatures can fluctuate depending primarily on wet bulb temperatures during specific seasons in specific locations around the globe.

[0049] According to one or more embodiments, the boost compressor **142** can be configured to elevate the pressure of the cooled recycle gas stream **140** to a pressure ranging from about 17 psia to about 21 psia. As a result, the main compressor **104** eventually receives and compresses a recycled exhaust with a higher density and increased mass flow, thereby allowing for a substantially higher discharge pressure while maintaining the same or similar pressure ratio. In order to further increase the density and mass flow of the recycle exhaust gas, the pressurized recycle gas in line **145** discharged from the boost compressor **142** can then be further cooled in the second cooling unit **136**. In one or more embodiments, the second cooling unit **136** can be configured to reduce the temperature of the pressurized recycle gas in line **145** to about 105 °F before being directed to the main compressor **104**.

[0050] In at least one embodiment, the temperature of the compressed recycle exhaust gas in line **144** discharged from the main compressor **104**, and consequently the temperature of the purge stream **146**, can be about 800 °F, with a pressure of around 280 psia. The addition of the boost compressor **142** and the stoichiometric combustion of enriched air can

increase the CO₂ purge pressure in the purge stream **146**, which can lead to improved solvent treating performance in the CO₂ separator **148** due to the higher CO₂ partial pressure.

[0051] Embodiments of the present disclosure can be further described with the following simulated example. Although the simulated example is directed to a specific embodiment, it is not to be viewed as limiting the disclosure in any specific respect.

[0052] To illustrate the superior performance of using enriched air as the compressed oxidant in line **114**, the system **100** was simulated using standard air and then using enriched air having an oxygen concentration of about 35wt% for the same gas turbine system **102** under the same ambient conditions. The following table provides these testing results and performance estimations.

TABLE 1

Triple -Cycle Performance Comparison		
Power (MW)	Cycle with Air	Cycle with Enriched Air
Gas Turbine Expander Power	1234	1386
Main Compressor	511	561
Fan or Boost Compressor	18	20
Inlet Compressor	251	176
Total Compression Power	780	757
Net Gas Turbine Power	444	616
Steam Turbine Net Power	280	316
Standard Machinery Net Power	724	931
Aux. Losses	16	18
Nitrogen Expander Power	181	109
Combined Cycle Power	889	1022
Combined Cycle Eff. (%lhv)	55.6	56.4

[0053] As should be apparent from Table 1, embodiments including enriched air as the compressed oxidant in line **114** can result in an increase in expander **106** power, due to an increased expansion pressure ratio and an increased mass flow through the expander **106**. Moreover, while the main compressor **104** may experience a slight increase in power demand, partially arising from the removal of a portion of the N₂ component from the air, the increase is more than offset by the reduced air compression power in the inlet compressor **118**, thereby resulting in an overall decrease in the total compression power required. As can be appreciated, because of the reduced airflow for the same amount of oxygen, the inlet compressor **118** can exhibit a considerable decrease in required compressor power.

Importantly, Table 1 indicates a large increase in the combined-cycle power output which reflects about 1.0% uplift in combined-cycle efficiency.

[0054] While the present disclosure may be susceptible to various modifications and alternative forms, the exemplary embodiments discussed above have been shown only by way of example. However, it should again be understood that the disclosure is not intended to be limited to the particular embodiments disclosed herein. Indeed, the present disclosure includes all alternatives, modifications, and equivalents falling within the true spirit and scope of the appended claims.

CLAIMS

What is claimed is:

1. A gas turbine system, comprising:
 - a first compressor configured to receive and compress a recycled exhaust gas into a compressed recycle exhaust gas;
 - a second compressor configured to receive and compress enriched air to generate a compressed oxidant;
 - a combustion chamber configured to receive the compressed recycle exhaust gas and the compressed oxidant and stoichiometrically combust a fuel stream, wherein the compressed recycle exhaust gas serves as a diluent to moderate combustion temperatures; and
 - an expander coupled to the first compressor and configured to receive a discharge from the combustion chamber to generate the recycled exhaust gas and at least partially drive the first compressor.
2. The system of claim 1, wherein the enriched air has an oxygen concentration between about 30wt% and about 50wt%.
3. The system of claim 2, wherein the enriched air is mixed with atmospheric air to obtain the oxygen concentration between about 30wt% and about 50wt%.
4. The system of claim 1, wherein the enriched air is derived from membrane separation, pressure swing adsorption, temperature swing adsorption, and any combination thereof.
5. The system of claim 1, wherein the enriched air is derived from a reject stream of an air separation unit.
6. The system of claim 5, wherein the reject stream has an oxygen concentration between about 50wt% and about 70wt%.
7. The system of claim 1, wherein the recycle exhaust gas has a CO₂ concentration of between about 10wt% and about 20wt%.
8. The system of claim 1, wherein the fuel stream is selected from the group consisting of: natural gas, methane, naphtha, butane, propane, syngas, diesel, kerosene, aviation fuel, coal derived fuel, bio-fuel, oxygenated hydrocarbon feedstock, and any combination thereof.
9. The system of claim 1, further comprising a purge stream taken from the compressed recycle exhaust gas and treated in a CO₂ separator to generate a CO₂ stream and a residual stream substantially comprising nitrogen gas.
10. A method of generating power, comprising:

compressing a recycled exhaust gas in a main compressor to generate a compressed recycle exhaust gas;

compressing enriched air in an inlet compressor to generate a compressed oxidant;

stoichiometrically combusting the compressed oxidant and a fuel in a combustion chamber and in the presence of the compressed recycle exhaust gas, thereby generating a discharge stream, wherein the compressed recycle exhaust gas acts as a diluent configured to moderate the temperature of the discharge stream; and

expanding the discharge stream in an expander to at least partially drive the main compressor and generate the recycled exhaust gas and at least partially drive the main compressor.

11. The method of claim 10, wherein the enriched air has an oxygen concentration between about 30wt% and about 50wt%.

12. The method of claim 11, further comprising mixing the enriched air with atmospheric air to obtain the oxygen concentration between about 30wt% and about 50wt%.

13. The method of claim 10, wherein the recycle exhaust gas has a CO₂ concentration of between about 10wt% and about 20wt%.

14. The method of claim 10, wherein the enriched air is derived from a reject stream of an air separation unit, the reject stream having an oxygen concentration between about 50wt% and about 70wt%.

15. An integrated system, comprising:

a gas turbine system, comprising:

a first compressor configured to receive and compress a recycled exhaust gas into a compressed recycle exhaust gas;

a second compressor configured to receive and compress enriched air to generate a compressed oxidant, the enriched air having an oxygen concentration between about 30wt% and about 50wt%;

a combustion chamber configured to receive the compressed recycle exhaust gas and the compressed oxidant and stoichiometrically combust a fuel stream, wherein the compressed recycle exhaust gas serves as a diluent to moderate combustion temperatures; and

an expander coupled to the first compressor and configured to receive a discharge from the combustion chamber to generate the recycled exhaust stream and at least partially drive the first compressor; and

an exhaust gas recirculation system, comprising:

a heat recovery steam generator communicably coupled to a steam gas turbine, the heat recovery steam generator being configured to receive the recycled exhaust gas from the expander to create steam that generates electrical power in the steam generator;

one or more cooling units configured to cool the recycled exhaust gas received from the heat recovery steam generator and remove condensed water from the recycled exhaust gas; and

a boost compressor configured to increase the pressure of the recycled exhaust gas before injection into the first compressor to provide the compressed recycle exhaust gas.

16. The system of claim 15, wherein the boost compressor increases the pressure of the recycled exhaust gas stream to a pressure between about 17 psia and about 21 psia.

17. The system of claim 15, wherein the recycle exhaust gas has a CO₂ concentration of between about 15wt% and about 20wt%.

18. The system of claim 15, wherein the enriched air is derived from membrane separation, pressure swing adsorption, temperature swing adsorption, an air separation unit, and any combination thereof.

19. The system of claim 18, wherein the air separation unit has a reject stream having an oxygen concentration between about 50wt% and about 70wt%, the reject stream substantially providing the enriched air.