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**LOW EMISSION POWER GENERATION SYSTEMS
AND METHODS INCORPORATING CARBON DIOXIDE
SEPARATION**

(57) Abstract:

Methods and systems for CO₂ separation in low emission power plants are provided. One system includes a gas turbine system that combusts a fuel and an oxidant in the presence of a compressed recycle stream to provide mechanical power and a gaseous exhaust. A purge stream is taken from the compressed recycle stream and directed to a CO₂ separator configured to absorb CO₂ from the purge stream using a potassium carbonate solvent. Volatiles are removed from the rich solvent by stripping or by flashing to an intermediate pressure before the rich solvent is regenerated and CO₂ is removed.

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(54) Title: LOW EMISSION POWER GENERATION SYSTEMS AND METHODS INCORPORATING CARBON DIOXIDE SEPARATION

(57) Abstract: Methods and systems for CO₂ separation in low emission power plants are provided. One system includes a gas turbine system that combusts a fuel and an oxidant in the presence of a compressed recycle stream to provide mechanical power and a gaseous exhaust. A purge stream is taken from the compressed recycle stream and directed to a CO₂ separator configured to absorb CO₂ from the purge stream using a potassium carbonate solvent. Volatiles are removed from the rich solvent by stripping or by flashing to an intermediate pressure before the rich solvent is regenerated and CO₂ is removed.

**LOW EMISSION POWER GENERATION SYSTEMS AND METHODS
INCORPORATING CARBON DIOXIDE SEPARATION**

CROSS REFERENCE TO RELATED APPLICATIONS

- 5 **[0001]** This application claims priority to U.S. Provisional Application 61/542,041 filed September 30, 2011 entitled, LOW EMISSION POWER GENERATION SYSTEMS AND METHODS INCORPORATING CARBON DIOXIDE SEPARATION; U.S. Provisional Application 61/466,384 filed March 22, 2011 entitled, LOW EMISSION TURBINE SYSTEMS HAVING A MAIN AIR COMPRESSOR OXIDANT CONTROL APPARATUS AND METHODS RELATED THERETO; U.S. Provisional Application 61/542,030 filed September 30, 2011 entitled, LOW EMISSION TURBINE SYSTEMS INCORPORATING INLET COMPRESSOR OXIDANT CONTROL APPARATUS AND METHODS RELATED THERETO; U.S. Provisional Application 61/466,385 filed March 22, 2011 entitled, METHODS FOR CONTROLLING STOICHIOMETRIC COMBUSTION ON A FIXED GEOMETRY GAS TURBINE SYSTEM AND APPARATUS AND SYSTEMS RELATED THERETO; U.S. Provisional Application 61/542,031 filed September 30, 2011 entitled, SYSTEMS AND METHODS FOR CONTROLLING STOICHIOMETRIC COMBUSTION IN LOW EMISSION TURBINE SYSTEMS; U.S. Provisional Application 61/466,381 filed March 22, 2011 entitled, METHODS OF VARYING LOW EMISSION TURBINE GAS RECYCLE CIRCUITS AND SYSTEMS AND APPARATUS RELATED THERETO; U.S. Provisional Application 61/542,035 filed September 30, 2011 entitled, METHODS OF VARYING LOW EMISSION TURBINE GAS RECYCLE CIRCUITS AND SYSTEMS AND APPARATUS RELATED THERETO; all of which are hereby incorporated by reference in their entirety
- 25 **[0002]** This application is related to U.S. Provisional Application 61/542,036 filed September 30, 2011 entitled, SYSTEMS AND METHODS FOR CARBON DIOXIDE CAPTURE IN LOW EMISSION TURBINE SYSTEMS; U.S. Provisional Application 61/542,037 filed September 30, 2011 entitled, SYSTEMS AND METHODS FOR CARBON DIOXIDE CAPTURE IN LOW EMISSION TURBINE SYSTEMS; U.S. Provisional Application 61/542,039 filed September 30, 2011 entitled, SYSTEMS AND METHODS FOR CARBON DIOXIDE CAPTURE IN LOW EMISSION COMBINED TURBINE

SYSTEMS; all of which are hereby incorporated by reference in their entirety.

FIELD OF THE DISCLOSURE

[0003] Embodiments of the disclosure relate to low emission power generation systems. More particularly, embodiments of the disclosure relate to methods and apparatus for
5 combustng a fuel for power generation and enhanced carbon dioxide (CO₂) manufacture, and employing solvent technology to capture the CO₂.

BACKGROUND OF THE DISCLOSURE

[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
10 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] Many oil producing countries are experiencing strong domestic growth in power demand and have an interest in enhanced oil recovery (EOR) to improve oil recovery from
15 their reservoirs. Two common EOR techniques include nitrogen (N₂) injection for reservoir pressure maintenance and carbon dioxide (CO₂) injection for miscible flooding for EOR. There is also a global concern regarding green house gas (GHG) emissions. This concern combined with the implementation of cap-and-trade policies in many countries makes reducing CO₂ emissions a priority for these and other countries as well as the companies that
20 operate hydrocarbon production systems therein.

[0006] Some approaches to lower CO₂ emissions include fuel de-carbonization or post-combustion capture using solvents, such as amines. However, both of these solutions are expensive and reduce power generation efficiency, resulting in lower power production, increased fuel demand and increased cost of electricity to meet domestic power demand. In
25 particular, the presence of oxygen, sulfur oxides (SO_x), and nitrogen oxide (NO_x) makes the use of amine solvent absorption very problematic. Another approach is an oxyfuel gas turbine in a combined cycle (*e.g.*, where exhaust heat from the gas turbine Brayton cycle is captured to make steam and produce additional power in a Rankine cycle). However, there are no commercially available gas turbines that can operate in such a cycle and the power
30 required to produce high purity oxygen significantly reduces the overall efficiency of the process.

[0007] Moreover, with the growing concern about global climate change and the impact of CO₂ emissions, emphasis has been placed on minimizing CO₂ emissions from power plants. Gas turbine power plants are efficient and have a lower cost compared to nuclear or coal power generation technologies. Capturing CO₂ from the exhaust of a gas turbine power plant is very expensive, however, because the concentration of CO₂ in the exhaust stack is low, a large volume of gas needs to be treated, and the pressure of the exhaust stream is low. These factors, among others, result in a high cost of CO₂ capture.

[0008] Capture and recovery of CO₂ from low emission power generation systems that incorporate an exhaust gas recycle loop has been previously described. For example, U.S. Patent Application Serial No. 61/361173, which is incorporated herein by reference in its entirety, illustrates the use of a potassium carbonate (K₂CO₃) solvent to absorb and recover CO₂ from such systems. When CO₂ is recovered via solvent absorption, however, the solvent also absorbs small quantities of volatile components (such as, for example, nitrogen, oxygen, argon, and carbon monoxide) that will have a small solubility in a water-based solvent such as K₂CO₃. Upon regeneration of the solvent to release the absorbed CO₂, these volatile components will also be evolved and will remain with the CO₂. If the CO₂ is used for EOR or is injected into a reservoir for sequestration, the presence of volatiles may be undesirable. For example, the presence of oxygen may increase corrosion rates, while the presence of carbon monoxide (CO) may result in safety or environmental hazards if released during startup or process upset conditions.

[0009] Accordingly, there is still a substantial need for a low emission, high efficiency power generation process with incorporated CO₂ capture and recovery at a reduced cost. Additionally, when a K₂CO₃ solvent is employed for CO₂ separation, there is also an interest in removing volatiles from the recovered CO₂.

SUMMARY OF THE DISCLOSURE

[0010] The present invention is directed to low emission power generation systems that incorporate an exhaust gas recycle loop and carbon dioxide (CO₂) capture and recovery using a potassium carbonate-based (K₂CO₃) separation system. In the low emission power generation systems described herein, exhaust gases from low emission gas turbines, which are vented in a typical natural gas combined cycle plant, are instead recycled and a portion of the recycled exhaust gas is separated and recovered. The apparatus, systems, and methods of

the invention separate the exhaust gas using a K_2CO_3 solvent to absorb and recover CO_2 . Such K_2CO_3 separation processes are sometimes referred to as hot potassium carbonate, or “hot pot” processes. Apparatus and methods for removing volatile components from the CO_2 -rich solvent prior to regeneration of the solvent and removal of CO_2 are further
5 incorporated herein, resulting in the production of high purity CO_2 with little to no contaminants. The recovered CO_2 may be used for enhanced oil recovery (EOR), sequestration, storage, or for a number of other purposes.

[0011] In the systems and methods of the present invention, fuel and a compressed oxidant are combusted in the presence of a compressed recycle stream in a combustion
10 chamber to generate a discharge stream. The discharge stream is expanded to produce power and generate a gaseous exhaust stream, and the gaseous exhaust stream is cooled and recirculated to the main compressor. The main compressor generates a compressed recycle stream. A portion of the compressed recycle stream is directed back to the combustion chamber to act as a diluent during combustion, while the remainder of the compressed
15 recycle stream is directed to a CO_2 separation system. Within the CO_2 separation system, the exhaust gases are cooled and directed to an absorption column, where a K_2CO_3 solvent is used to absorb CO_2 from the exhaust gases, generating a nitrogen-rich residual stream and a bicarbonate solvent solution.

[0012] In one or more embodiments of the invention, volatile components are removed
20 from the bicarbonate solvent solution by stripping the solvent solution with a vapor such as nitrogen, argon, or steam. In other embodiments, volatile components are removed from the bicarbonate solvent solution by flashing the solvent solution to a pressure sufficient to release gaseous volatiles from the solvent while keeping the CO_2 in the liquid solution. The volatile components may then be recycled to the exhaust gas recirculation (EGR) system, such as by
25 combining the volatiles with the cooled recycle stream entering the main compressor. In both scenarios, once volatiles have been removed from the bicarbonate solvent solution, the solution is flashed to atmospheric or near-atmospheric pressure and regenerated by boiling the bicarbonate solvent solution to remove CO_2 and water, producing a lean regenerated K_2CO_3 solvent. The regenerated solvent may be recycled to the absorption column, while the
30 CO_2 and water removed from the solvent solution may be cooled and condensed to generate a water stream and a recovered CO_2 stream. By removing volatiles from the bicarbonate solvent solution before regenerating the solvent and recovering CO_2 , a higher purity CO_2

product is obtained.

BRIEF DESCRIPTION OF THE DRAWINGS

[0013] The foregoing and other advantages of the present disclosure may become apparent upon reviewing the following detailed description and drawings of non-limiting
5 examples of embodiments in which:

[0014] FIG. 1 depicts an integrated system for low emission power generation and enhanced CO₂ recovery.

[0015] FIG. 2 depicts an illustrative CO₂ capture system used in an integrated system for low emission power generation and enhanced CO₂ recovery.

10 [0016] FIG. 3 depicts another illustrative CO₂ capture system incorporating a stripping section to remove volatiles prior to regeneration of the bicarbonate solvent solution and removal of CO₂.

[0017] FIG. 4 depicts another illustrative CO₂ capture system incorporating a flash step to remove volatiles prior to regeneration of the bicarbonate solvent solution and removal of
15 CO₂.

[0018] FIG. 5 depicts an integrated system for low emission power generation and enhanced CO₂ recovery in which volatiles removed in the CO₂ capture system are recycled to the exhaust gas recirculation system.

DETAILED DESCRIPTION OF THE DISCLOSURE

20 [0019] 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
25 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.

[0020] 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.

[0021] 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.

[0022] 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 an equivalence ratio ranging from about 0.9:1 to about 1.1:1, or more preferably from about 0.95:1 to about 1.05:1.

[0023] 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.

[0024] As used herein, the phrase “near-atmospheric pressure” refers to a pressure within about 10 percent, or preferably within about 5 percent, of the actual atmospheric pressure. For example, if atmospheric pressure is 14.7 psi, any pressure within the range of about 13.2 psi to about 16.2 psi is considered to be “near-atmospheric pressure.”

[0025] Embodiments of the presently disclosed systems and processes may be used to produce ultra low emission electric power and CO_2 for EOR or sequestration applications. According to some embodiments disclosed herein, a mixture of air and fuel can be combusted and simultaneously mixed with a stream of recycled exhaust gas. The stream of recycled exhaust gas is cooled and compressed and may be used as a diluent to control or otherwise moderate the temperature of the combustion and of the exhaust gas entering the succeeding expander. In one or more embodiments, the combustion conditions are non-stoichiometric. In other embodiments, the combustion conditions are stoichiometric or substantially

stoichiometric.

[0026] The exhaust gases not recycled to the combustion chamber are separated to capture CO₂ and generate a residual stream comprising nitrogen. In EOR applications, the recovered CO₂ is injected into or adjacent to producing oil wells, usually under supercritical conditions. The CO₂ acts as both a pressurizing agent and, when dissolved into the underground crude oil, significantly reduces the oil's viscosity enabling the oil to flow more rapidly through the earth to a removal well. The residual stream comprising nitrogen (and frequently oxygen and argon as well) may be used to generate additional power, and may also be used for a variety of purposes, including for pressure maintenance. In pressure maintenance applications, an inert gas such as nitrogen is compressed and injected into a hydrocarbon reservoir to maintain the original pressure in the reservoir, thus allowing for enhanced recovery of hydrocarbons. The result of the systems disclosed herein is the production of power and the concentration and capture of CO₂ in a more economically efficient manner.

[0027] Combustion at near stoichiometric conditions (or "slightly rich" combustion) can prove advantageous in order to eliminate the cost of excess oxygen removal. By cooling the exhaust gas and condensing the water out of the stream, a relatively high content CO₂ 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 electric power can be produced with little or no SO_x, NO_x, or CO₂ being emitted to the atmosphere. The result of this process is the production of power and the manufacturing of additional CO₂.

[0028] Stoichiometric or substantially stoichiometric combustion of the fuel combined with a boost in the pressure of the exhaust gas prior to being compressed for recirculation can make the CO₂ partial pressure much higher than in conventional gas turbine exhaust. As a result, carbon capture in a CO₂ separation process can be undertaken using less energy-intensive solvents, such as potassium carbonate (K₂CO₃). The presence of oxygen (O₂), sulfur oxides (SO_x), and nitrogen oxides (NO_x) in the exhaust gas make the use of amine solvents (*e.g.*, MEA, DEA, MDEA, and related solvents) difficult, even with the higher pressure and increased CO₂ content, since amine solvents can degrade in their presence. Moreover, K₂CO₃ easily absorbs SO_x and NO_x, converting them to simple fertilizers such as potassium sulfite (K₂SO₃) and potassium nitrate (KNO₃). These fertilizers can be easily

discharged in an environmentally harmless manner.

[0029] In one or more embodiments of the present invention, integrated power generation systems are provided comprising a gas turbine system, an exhaust gas recirculation system, and a CO₂ separation system. Various embodiments of each of these components are
5 described in more detail below.

Gas Turbine System

[0030] The gas turbine system comprises a combustion chamber, an inlet compressor, and an expander, where the combustion chamber is configured to combust one or more compressed oxidants and one or more fuels in the presence of a compressed recycle stream to
10 generate a discharge stream. The discharge stream is expanded in an expander to generate a gaseous exhaust stream. The one or more oxidants may comprise any oxygen-containing fluid, such as ambient air, oxygen-enriched air, substantially pure oxygen, or combinations thereof. The one or more fuels may comprise natural gas, associated gas, diesel, fuel oil, gasified coal, coke, naphtha, methane, ethane, butane, propane, syngas, kerosene, aviation
15 fuel, bio-fuel, oxygenated hydrocarbon feedstock, other suitable hydrocarbon containing gases or liquids, hydrogen, carbon monoxide, or combinations thereof. Additionally, the fuel may comprise inert components including but not limited to N₂ or CO₂. In some embodiments, the fuel may be at least partially supplied by a hydrocarbon reservoir that is benefitting from EOR via injection of CO₂ captured using the process described herein. In
20 certain embodiments, the fuel comprises natural gas.

[0031] In one or more embodiments, the combustion conditions in the combustion chamber are stoichiometric or substantially stoichiometric. A diluent may be supplied to the combustion chamber to control or otherwise regulate the temperature of the combustion and flue gas to meet the material requirements of the succeeding expander. The flow of the
25 diluent may be adjusted to help maintain stoichiometric conditions in the combustion chamber, moderating changes in composition, volumetric flow, or other variations in the oxidant and fuel streams. In one or more embodiments, the diluent provided to the combustion chamber comprises at least a portion of the compressed recycle stream.

[0032] In some embodiments, high pressure steam may also be employed as a diluent in
30 the combustion chamber. In such embodiments, the addition of steam would reduce power and size requirements in the system, but would require the addition of a water recycle loop.

[0033] Additionally, in further embodiments, the compressed oxidant feed to the combustion chamber may comprise argon. For example, the oxidant may comprise from about 0.1 to about 5.0 vol% argon, or from about 1.0 to about 4.5 vol% argon, or from about 2.0 to about 4.0 vol% argon, or from about 2.5 to about 3.5 vol% argon, or about 3.0 vol% argon.

[0034] The inlet compressor may be a single compressor or two or more compressors operating in parallel or in series. Each compressor may comprise a single stage or multiple stages. In multiple stage compressors, interstage cooling may optionally be employed to allow for higher overall compression ratios and higher overall power output. When more than one compressor is used to compress the oxidant stream, the compressors taken together are considered herein to be the “inlet compressor.” The inlet compressor may be of any type suitable for the process described herein. Such compressors include, but are not limited to, axial, centrifugal, reciprocating, or twin-screw compressors and combinations thereof. In one or more embodiments, the inlet compressor comprises an axial compressor.

[0035] Combustion of the oxidant and fuel in the combustion chamber generates a discharge stream. The discharge stream comprises products of combustion, and their individual compositions will vary depending upon the composition of the fuel and the oxidant used in the combustion chamber. In one or more embodiments, the discharge stream may comprise vaporized water, CO₂, O₂, carbon monoxide (CO), nitrogen (N₂), argon (Ar), NO_x, SO_x, hydrogen sulfide (H₂S), or combinations thereof. The discharge stream may be expanded in the expander to form a gaseous exhaust stream.

[0036] The expander may be a single expander or two or more expanders operating in parallel or in series. Each expander may comprise a single stage or multiple stages. When more than one expander is used to expand the discharge stream, the expanders taken together are considered herein to be the “expander.” The expander may be of any type suitable for the process described herein, including but not limited to axial or centrifugal expanders or combinations thereof. Expansion of the discharge stream generates power, which may be used to drive one or more compressors or electric generators. In one or more embodiments of the invention, the expander is coupled to the main compressor, described in further detail below, via a common shaft or other mechanical, electrical, or other power coupling, such that the main compressor is at least partially driven by the expander. In other embodiments, the main compressor may be mechanically coupled to an electric motor with or without a speed

increasing or decreasing device such as a gear box. When taken together, the main compressor, combustion chamber, and expander may be characterized as a Brayton cycle.

Exhaust Gas Recirculation (EGR) System

[0037] The exhaust gas recirculation (EGR) system comprises a boost compressor or
5 blower and one or more cooling units fluidly coupled to the boost compressor, where the
boost compressor is configured to receive and increase the pressure of the gaseous exhaust
stream and the one or more cooling units are configured to cool the gaseous exhaust stream
and provide a cooled recycle stream to a main compressor. The main compressor compresses
the cooled recycle stream and generates a compressed recycle stream. At least a portion of
10 the compressed recycle stream is directed back to the combustion chamber, while a purge
stream comprising another portion of the compressed recycle stream is cooled to generate a
cooled purge stream that is directed to the CO₂ separation system.

[0038] The boost compressor (or blower) and the one or more cooling units may be
arranged in any fashion suitable for the intended purpose. For example, the one or more
15 cooling units may be located upstream or downstream of the boost compressor, or may be
located both upstream and downstream of the boost compressor. The one or more cooling
units may be any type of apparatus suitable for lowering the temperature of the exhaust gases,
such as for example a heat recovery unit (HRU), heat exchanger, regenerator, direct contact
cooler (DCC), trim cooler, mechanical refrigeration unit, or combinations thereof. In some
20 embodiments, the cooling unit is an HRU, which may be located upstream of the boost
compressor. When used, the HRU may be configured to receive the gaseous exhaust stream
and utilize the residual heat in the stream to generate steam, such as in a heat recovery steam
generator (HRSG). The steam generated by the HRSG may be used for a variety of purposes,
such as to drive a steam turbine generator in a Rankine cycle or for water desalination. In the
25 same or other embodiments, the cooling unit is a DCC, which may be located upstream or
downstream of the boost compressor. When used, the DCC may be configured to remove a
portion of condensed water from the cooled recycle stream via a water dropout stream. In
some embodiments, the water dropout stream may optionally be routed to a HRSG to provide
a water source for the generation of additional steam. In some embodiments, both a HRSG
30 and a DCC are used to cool the gaseous exhaust stream and are each located upstream of the
boost compressor.

[0039] In one or more embodiments, the cooled recycle stream is directed to the main compressor and compressed to generate a compressed recycle stream. The main compressor may be a single compressor or two or more compressors operating in parallel or in series. Each compressor may comprise a single stage or multiple stages. In multiple stage
5 compressors, interstage cooling may optionally be employed to allow for higher overall compression ratios and higher overall power output. When more than one compressor is used to compress the cooled recycle stream, the compressors taken together are considered herein to be the “main compressor.” The main compressor may be of any type suitable for the process described herein. Such compressors include, but are not limited to, axial, centrifugal,
10 reciprocating, or twin-screw compressors and combinations thereof. In one or more embodiments, the main compressor comprises an axial compressor. Cooling and compressing the exhaust gases helps to address issues related to the large volume of gas that must be treated and the low pressure of the exhaust streams that ordinarily lead to a high cost of CO₂ capture, thus making CO₂ capture and recovery in the present systems more efficient
15 and more cost effective.

[0040] Upon exiting the main compressor, the compressed recycle stream may be directed to the combustion chamber for use as a diluent to control or otherwise regulate the temperature of the combustion and flue gas to meet the material requirements of the succeeding expander and, when desired, to maintain stoichiometric combustion conditions in
20 the combustion chamber. In one or more embodiments, a purge stream may be diverted from the compressed recycle stream and directed to a CO₂ separation system. It will be recognized by those skilled in the art that intermediate heating, cooling, or other process operations may be required so that the purge stream enters the CO₂ separation system at conditions optimized for the particular separation process employed. In one or more embodiments, for example, a
25 heat exchanger or other cooling unit may be used to cool the purge stream to generate a cooled purge stream that is directed to the CO₂ separation system. The heat exchanger may employ any cooling fluid suitable to effect the desired amount of cooling, including but not limited to seawater, chilled water, one or more refrigerants, other process streams, or combinations thereof. In some embodiments, the purge stream may be cooled in a cross
30 exchanger configured to use the nitrogen-rich residual stream exiting the absorption column of the CO₂ separation system for cooling. In embodiments in which the residual stream is later expanded to generate power, cross exchanging the purge and residual streams may be

especially advantageous because the additional heat provided to the residual stream may allow for increased power generation.

Carbon Dioxide Separation System

[0041] The combination of stoichiometric combustion (when used) in the combustion chamber and water removal through the one or more cooling units allows the CO₂ content in the exhaust gas to accumulate to about 10 vol% or higher, which is higher than exhaust gases in conventional combined-cycle systems. These effects, plus the impact of higher pressures resulting from the implementation and of a boost compressor, make the CO₂ partial pressure much higher than conventional gas turbine exhaust. Consequently, this allows for carbon capture in the CO₂ separation system using less energy-intensive solvents, such as K₂CO₃ solvent technology.

[0042] The presence of O₂, SO_x, and NO_x make the use of amine solvents (*e.g.*, MEA, DEA, MDEA, and related solvents) difficult, even with higher pressure and increased CO₂ content, since these gases can cause amine degradation. Potassium carbonate, however, is non-reactive and immune to any effects of oxygen. Although the reaction undertaken in the combustion chamber may, in some embodiments, be stoichiometric, a fraction of O₂ may nonetheless be present in the cooled purge stream due to combustion equilibrium limitations. While MEA solvents will require significant solvent reclamation and safe disposal, the use of K₂CO₃ eliminates oxygen-based solvent degradation.

[0043] Potassium carbonate easily absorbs SO_x or NO_x in the exhaust gas, converting these compounds to simple fertilizers, such as potassium sulfite (K₂SO₃) and potassium nitrate (KNO₃). In particular, SO₂, SO₃, and NO₂ all form fairly strong acids in water, much stronger than CO₂. Thus, they will be preferentially absorbed in the solvent solution, but will become heat stable salts (HSS) and will not be removed by regeneration. On the other hand, NO and N₂O have low solubility and are more difficult to absorb than NO₂, and tend to occur at lower concentrations. As simple fertilizers, the K₂SO₃ and KNO₃ can be easily discharged in an environmentally harmless manner, so long as no other toxic compounds, such as corrosion inhibitors, activators, etc., are added to the solvent system. When the sulfate and nitrate compounds are removed, potassium hydroxide (KOH) can be added for solvent makeup. Since potassium hydroxide is a fairly inexpensive chemical, this can be accomplished rather economically.

[0044] Accordingly, in one or more embodiments, the CO₂ separation system comprises an absorption column configured to absorb CO₂ from the cooled purge stream using a K₂CO₃ solvent. As CO₂ is absorbed by the K₂CO₃ in the absorption column, it reacts with water to form carbonic acid (H₂CO₃), and then bicarbonate (HCO₃⁻). The acidic part of the carbonic acid (H⁺) can react with the carbonate ion (CO₃⁻²) to form an additional bicarbonate ion. Thus, the overall reaction can be as follows:



As a result, the absorption column generates a nitrogen-rich residual stream and a bicarbonate solvent solution as described above.

[0045] The nitrogen-rich residual stream from the absorption column may be used, wholly or in part, for a variety of applications. For example, the residual stream may be injected into a hydrocarbon reservoir for pressure maintenance. The residual stream may also be sold, stored, or vented. In one or more embodiments when pressure maintenance is not a viable option (or when only a portion of the residual stream is required for pressure maintenance), the residual stream may be cooled, by expansion or another method, and used to provide refrigeration in the systems described herein. For example, the cooled residual stream may be used to provide refrigeration to reduce the suction temperature of one or more compressors within the system, or to chill water for use in one or more cooling units within the system.

[0046] In other embodiments when all or part of the residual stream is not used for pressure maintenance, the residual stream may instead be heated prior to expansion in a turbine so that additional power may be generated for use elsewhere in the system or for sale. Some methods of heating the residual stream include cross-exchanging the residual stream with another process stream (such as the purge stream, as described above, or another stream within the separation system or in the overall power generation system) in a heat exchanger or using a supplementary combustor to supply additional heat to the residual stream. It will be appreciated that the use of an additional combustor will require additional fuel. If a carbon-containing fuel is used in the combustor, additional CO₂ will be generated that will be unrecoverable from the residual stream. Therefore, in some embodiments, the fuel used in the combustor may be a non-carbon fuel source, such as hydrogen. The oxidant required by the supplementary combustor may be supplied via a separate oxidant stream, or there may be

sufficient oxidant in the residual stream such that an additional supply of oxidant is unnecessary. Other possible methods for heating the absorption column residual stream include using a heating coil in a HRSG to heat the residual stream, using catalysis to combust any CO present in the residual stream, or heating the stream as a consequence of using the residual stream for cooling (i.e., as the residual stream provides cooling to other streams or apparatus, the stream itself is heated).

[0047] In one or more embodiments, the bicarbonate solvent solution exiting the absorption column is flashed to near-atmospheric pressure via a valve or other pressure-reducing device. In some embodiments, the pressure-reducing device may be a hydraulic turbine configured to generate additional power. Once flashed to near-atmospheric pressure, the bicarbonate solvent solution may be boiled in a regeneration column to remove CO₂ and water, producing a regenerated potassium carbonate solvent that may be recycled to the absorption column.

[0048] In some embodiments, the regeneration column may operate at temperatures exceeding the boiling point of water. For example, the regeneration column can operate in a temperature range from a lower limit of about 220 °F, or about 230 °F, or about 240 °F, to an upper limit of about 280 °F, about 290 °F, or about 300 °F. In the same or other embodiments, the regeneration column can operate at pressures ranging from about 0 psig to about 10 psig. In at least one embodiment, the regeneration column can be configured to operate at a pressure of about 3 psig.

[0049] The regeneration column can be configured to use steam circulating therein to boil the bicarbonate solvent and reverse the reaction undertaken in the absorption column, thereby yielding a regenerated, lean potassium carbonate solvent suitable for recirculation to the absorption column. In at least one embodiment, an in-line pump or the like may be used to drive at least a portion of the lean potassium carbonate solvent back to the absorption column.

[0050] In one or more embodiments, a portion of the lean potassium carbonate solvent recirculated to the absorption column may optionally be removed as a heat stable salt (HSS). Illustrative HSSs can include compound fertilizers, including but not limited to potassium sulfite and/or potassium nitrate. In order to make up for the loss of potassium carbonate content when an HHS is removed, and to maintain overall solution strength, a stream of potassium hydroxide can be subsequently supplied to the lean potassium carbonate stream

being directed to the absorption column or to the absorption column itself. In one or more embodiments, the potassium hydroxide serves as a solvent makeup.

[0051] The lean potassium carbonate solvent directed to the absorption column may optionally be directed through a first cooling unit before entering the absorption column. In one or more embodiments, the first cooling unit can be, for example, an air cooler or radiator-type heat exchanger, configured to reduce the temperature of the solvent. If used, the first cooling unit can be configured to reduce the temperature of the lean potassium carbonate solvent to temperatures ranging from about 230 °F to about 60 °F.

[0052] In order to generate the steam circulating in the regeneration column and maintain the required heat of regeneration, in one or more embodiments the regeneration column further comprises a reboiler fluidly coupled to the regeneration column. The reboiler can be configured to heat at least a portion of the lean potassium carbonate solvent not recirculated to the absorption column to produce a heated lean potassium carbonate solvent. The heated lean potassium carbonate solvent may then be recycled to the regeneration column to produce steam for boiling the bicarbonate solvent solution. In at least one embodiment, the reboiler can be supplied with heat from the HRSG in the EGR system. In other embodiments, however, the reboiler can be supplied with heat from another source, such as from the intermediate extraction or discharge of a steam turbine.

[0053] The water included in the cooled purge stream can condense into the bicarbonate solvent solution in the absorption column and subsequently boil out in the regeneration column. Consequently, the regeneration column can further discharge the CO₂ separated from the solvent during the regeneration process and any residual water via an overhead stream. In at least one embodiment, the CO₂ (which is typically a vapor) and residual water can be directed through a second cooling unit, such as an air cooler or radiator-type heat exchanger, before being introduced to a condenser or other separation vessel. The condenser can be configured to separate the residual water from any recovered CO₂ to generate a water stream and a stream comprising primarily CO₂.

[0054] In some embodiments, at least a portion of the water exiting the condenser may be recirculated back into the regeneration column to allow the balance of water in the system to be maintained. Water is constantly introduced into the solvent via the cooled purge stream, and subsequently removed via the condenser. In order to maintain solvent conditions and

strength, the water must remain in balance within the CO₂ separation system. Accordingly, the water recirculated to the regeneration column can allow water to be returned so that steam generated by the reboiler can be controlled independently of this water balance. In other words, the recirculated water can be used as feedwater for the generation of steam in the regeneration column or to raise low pressure steam from feed cooling. In the same or other
5 embodiments, a portion of the water exiting the condenser can be disposed of as fresh process water. For example, although it may in some embodiments contain a portion of dissolved CO₂, the water exiting the condenser can be used for irrigation water, treated to be used for boiler feed water, and/or uses as clean process water.

10 **[0055]** In some embodiments, the separated CO₂ exiting the condenser can be subsequently compressed for applications such as CO₂ sequestration or storage, enhanced oil recovery, CO₂ sales, carbon capture, and/or combinations thereof. In one or more embodiments, the CO₂ stream exiting the condenser is of high purity, and comprises at least 95 mol% CO₂, or at least 98 mol% CO₂, or at least 99 mol% CO₂, or at least 99.5 mol% CO₂.

15 *Removal of Volatile Components*

[0056] When CO₂ is recovered via solvent absorption as described herein, the solvent may also absorb small quantities of volatile components (such as, for example, N₂, O₂, Ar, and CO) that will have a small solubility in a water-based solvent such as K₂CO₃. Upon regeneration of the solvent to release the absorbed CO₂, these volatile components are also
20 evolved and remain with the CO₂. In certain situations, such as when the CO₂ is used for EOR or is injected into a reservoir for sequestration, the presence of volatiles may be undesirable. For example, the presence of oxygen may increase corrosion rates, while the presence of CO may result in safety or environmental hazards if the CO₂ were released during startup or process upset conditions.

25 **[0057]** Accordingly, in certain embodiments of the present invention, the rich bicarbonate solvent solution exiting the absorption column is treated at an elevated pressure or intermediate pressure to remove volatile components before the solution is flashed to near-atmospheric pressure and regenerated in the regeneration column. The volatile components removed may include, but are not limited to, O₂, N₂, Ar, and CO. Two methods for removing
30 volatiles, stripping with vapor and two-stage flashing, are described herein. It will be appreciated by those skilled in the art that variations on these methods may also be effective

for removing volatiles from the bicarbonate solvent solution, and any such methods designed to remove volatiles from the solution without also removing CO₂ (or while removing only a negligible amount of CO₂) are considered to be within the scope of the present invention.

Vapor Stripping

5 **[0058]** In one or more embodiments of the present invention, volatiles are removed from the rich bicarbonate solvent solution by stripping the solvent with a vapor in a stripping column or stripping section. The vapor may be any (preferably clean) vapor that does not interact with the CO₂ in the solvent solution. Suitable vapors may include, but are not limited to, nitrogen, argon, steam, and combinations thereof.

10 **[0059]** In one or more embodiments, a stripping section is incorporated as additional stages within the absorption column (generally at the bottom of the column), such that the vapor stream enters the absorption column at or near the bottom stage of the column, while the cooled purge stream is fed to the middle of the column just above the stripping stages. The rich bicarbonate solvent solution, having been stripped of volatiles, exits the bottom of
15 the absorption column, while the stripping vapor (comprising the volatiles removed from the solvent) continues up the absorption column and exits the column as part of the nitrogen-rich residual stream.

20 **[0060]** In other embodiments, the stripping section may be an additional column separate from the absorption column. In such embodiments, a vapor stream is fed to or near the bottom of the stripping column, and rich bicarbonate solvent exiting the absorption column is fed to or near the top of the stripping column. In this manner, the vapor and the bicarbonate solvent solution flow countercurrently through the stripping column. The stripping column therefore generates a first (or overhead) stream comprising the stripping vapor and the volatiles removed from the bicarbonate solvent solution and a second (or bottom) stream
25 comprising bicarbonate solvent solution that has been stripped of volatiles. The overhead stream may be recycled to the absorption column, such that the stripping vapor (comprising the volatiles removed from the solvent) exits the absorption column as part of the nitrogen-rich residual stream.

30 **[0061]** In either scenario, stripping of the bicarbonate solvent solution takes place at an elevated pressure generally at or near the pressure of the cooled purge stream entering the absorption column. By stripping the rich bicarbonate solvent at an elevated pressure,

volatiles are removed from the solvent solution while essentially all of the CO₂ remains in the bicarbonate solution stream exiting the stripping section or column. The bicarbonate solvent solution may then be flashed via a valve or other pressure-reducing device (such as a hydraulic turbine) to near-atmospheric pressure and directed to the regeneration column. By removing the volatiles in this manner (i.e., prior to flashing the solvent solution to near-atmospheric pressure and regenerating the solvent), a pure or nearly pure CO₂ stream may be recovered from the CO₂ separation system.

[0062] As described above, when a stripping section or column is employed, the stripping vapors will exit the absorption column in the nitrogen-rich residual stream. It will be appreciated that further processing of this stream may be required to account for the vapors present in the stream. Additionally, in embodiments in which the nitrogen-rich residual stream is expanded to generate power, it may be desirable to pass the residual stream over an oxidizing catalyst so that no CO is emitted when or if the residual stream is later vented. Excess oxygen may be added to the stream prior to entering the oxidizing catalyst to ensure full combustion of any CO. Such combustion will advantageously further heat the residual stream, thus allowing for increased power generation.

Two-Stage Flash

[0063] In one or more other embodiments, instead of using a stripping column or section to remove volatiles, the rich bicarbonate solvent solution exiting the absorption column may instead be flashed via a valve or other pressure-reducing device to an intermediate (or reduced) pressure between the pressure of the cooled purge stream and atmospheric pressure. By flashing to a reduced but still elevated pressure, the bicarbonate solvent solution becomes a dual-phase stream comprising a gaseous phase and a liquid phase. In one or more embodiments, the reduced pressure to which the solvent is flashed is selected so that the gaseous phase comprises the volatile components in the solution (such as nitrogen, oxygen, argon, carbon monoxide, and combinations thereof), while essentially all of the CO₂ remains in the liquid phase of the solution. In some embodiments, for example, the gaseous phase of the bicarbonate solvent solution comprises less than about 5 mol%, or less than about 3 mol%, or less than about 2 mol%, or less than about 1 mol%, or less than about 0.5 mol%, or less than about 0.1 mol% CO₂.

[0064] In certain embodiments, the dual-phase solvent solution may be directed to a flash

vessel or other separation device configured to separate the gaseous volatiles from the liquid bicarbonate solvent solution comprising the CO₂. In some embodiments, at least about 95 mol%, or at least about 97 mol%, or at least about 98 mol%, or at least about 99 mol% of the total CO₂ entering the flash vessel remains in solution and is removed with the liquid bicarbonate solvent solution from the flash vessel. The volatiles exiting the flash vessel may then be recycled to the exhaust gas recirculation system. For example, the volatiles may be recycled and combined with the cooled recycle stream upstream of the main compressor. By recycling the volatiles in this manner, CO and O₂ may be re-used for combustion, thus increasing the efficiency of the power generation system. Additionally, if any CO₂ is removed with the volatiles, it is recompressed and reprocessed through the CO₂ separation system for recovery.

[0065] In one or more embodiments, the bicarbonate solvent solution exiting the flash vessel may be flashed via a second valve or other pressure-reducing device to near-atmospheric pressure and directed to the regeneration column. By removing the volatiles in this manner (i.e., at an intermediate pressure and prior to flashing the solvent solution to near-atmospheric pressure and regenerating the solvent), a pure or nearly pure CO₂ stream may be recovered from the CO₂ separation system.

[0066] As may be appreciated by those skilled in the art, selection of the method and apparatus used to remove volatiles from the rich bicarbonate solvent solution may be influenced by a variety of factors. For example, the intended use of the nitrogen-rich residual stream exiting the absorption column may help determine which of the volatiles removal methods is preferred. As described previously, the use of vapor stripping to remove volatiles may be advantageous in embodiments where the nitrogen-rich residual stream is expanded to generate power, particularly when the residual stream is passed over an oxidizing catalyst to combust CO. Such combustion will further heat the residual stream, thus allowing for increased power generation. Alternatively, when the nitrogen-rich residual stream is used for pressure maintenance in hydrocarbon reservoirs, removal of volatiles via the two-stage flash described above may be preferred. By recycling the volatiles removed from the bicarbonate solvent to the EGR in the two-stage flash method rather than combining the volatiles with the residual stream (as in the vapor stripping method), fuel efficiency is maximized because all of the fuel and/or oxidant value in the volatiles is recycled and recovered.

[0067] Referring now to the figures, embodiments of the invention may be best

understood with reference to a base case, depicted in FIGs. 1 and 2. FIG. 1 depicts a schematic of an illustrative integrated system **100** for power generation and CO₂ recovery. 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**.

[0068] The gas turbine system **102** can also include a combustion chamber **110** configured to combust a fuel in line **112** mixed with a compressed oxidant in 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, hydrogen, carbon monoxide, or combinations thereof. The compressed oxidant in 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 **120**. In one or more embodiments, the feed oxidant **120** can include any suitable gas containing oxygen, such as air, oxygen, oxygen-rich air, or combinations thereof.

[0069] As will be described in more detail below, the combustion chamber **110** can also receive a compressed recycle stream **144**, including an exhaust gas primarily having CO₂ and nitrogen components. The compressed recycle stream **144** can be derived from the main compressor **104** and may in some embodiments be adapted to help facilitate the stoichiometric or substantially stoichiometric combustion of the compressed oxidant in line **114** and fuel in line **112**, and also to increase the CO₂ concentration in the exhaust gas. An exhaust gas in line **116** 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 stream **144**. In at least one embodiment, the fuel in line **112** can be primarily natural gas, thereby generating an exhaust gas in line **116** including 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 or other compounds may also be present in the exhaust gas in line **116** due to combustion equilibrium limitations. The exhaust gas in line **116** can be directed to the inlet of the expander **106**. As the exhaust gas in line **116** expands through the expander **106**, it generates mechanical power to drive the main compressor **104** and also produce a
5 gaseous exhaust in line **122** having a heightened CO₂ content resulting from the influx of the compressed recycle exhaust gas in line **144**.

[0070] 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. The gaseous exhaust in line **122**
10 can be sent to the HRSG **126** in order to generate steam in line **130** and a cooled exhaust gas in line **132**. In some embodiments, the steam in line **130** can be sent to a steam turbine (not shown) to generate additional electrical power or to the CO₂ separator **148** to provide reboiler heat. In such embodiments, the combination of the HRSG **126** and the steam turbine can be characterized as a Rankine cycle. In combination with the gas turbine system **102**, the HRSG
15 **126** and the steam turbine, when included, can form part of a combined-cycle power generating plant, such as a natural gas combined-cycle (NGCC) plant.

[0071] The cooled exhaust gas in line **132** can be sent to at least one cooling unit **134** configured to reduce the temperature of the cooled exhaust gas in line **132** and generate a cooled recycle gas stream **140**. In one or more embodiments, the cooling unit **134** can be a
20 direct contact cooler, trim cooler, a mechanical refrigeration unit, or combinations thereof. The cooling unit **134** can also be configured to remove a portion of condensed water via a water dropout stream (not shown) which can, in at least one embodiment, be routed to the HRSG **126** to provide a water source for the generation of additional steam in line **130**. In one or more embodiments, the cooled recycle gas stream **140** can be directed to a boost
25 compressor **142** fluidly coupled to the cooling unit **134**. Cooling the cooled exhaust gas in line **132** in the cooling unit **134** can reduce the power required to compress the cooled recycle gas stream **140** in the boost compressor **142**.

[0072] The boost compressor **142** can be configured to increase the pressure of the cooled recycle gas stream **140** before it is introduced into the main compressor **104**. As opposed to a
30 conventional fan or blower system, the boost compressor **142** increases the overall density of the cooled recycle gas stream **140**, thereby directing an increased mass flow rate for the same volumetric flow to the main compressor **104**. Because the main compressor **104** is typically

volume-flow limited, directing more mass flow through the main compressor **104** can result in a higher discharge pressure from the main compressor **104**, thereby translating into a higher pressure ratio across the expander **106**. A higher pressure ratio generated across the expander **106** can allow for higher inlet temperatures and, therefore, an increase in power and efficiency of expander **106**. This can prove advantageous since the CO₂-rich exhaust gas in line **116** generally maintains a higher specific heat capacity.

[0073] The main compressor **104** can be configured to compress the cooled recycle gas stream **140** received from the boost compressor **142** to a pressure nominally above the combustion chamber **110** pressure, thereby generating the compressed recycle stream **144**. In at least one embodiment, a purge stream **146** can be diverted from the compressed recycle stream **144** and subsequently treated in a CO₂ separator **148** to capture CO₂ via line **150**. The separated CO₂ in line **150** can be used for sales, used in another process requiring carbon dioxide, and/or compressed and injected into a terrestrial reservoir for enhanced oil recovery (EOR), sequestration, or another purpose.

[0074] A residual stream **151**, essentially depleted of CO₂ and consisting primarily of nitrogen, can be derived from the CO₂ separator **148**. In one or more embodiments, the residual stream **151** can be expanded in a gas expander (not shown), such as a power-producing nitrogen expander fluidly coupled to the CO₂ separator **148**. In such embodiments, the gas expander can be optionally coupled to the inlet compressor **118** through a common shaft or other mechanical, electrical, or other power coupling, thereby allowing a portion of the power generated by the gas expander to drive the inlet compressor **118**. The residual stream **151**, whether expanded as described herein or not, can be vented to the atmosphere or implemented into other downstream applications known in the art. For example, the expanded nitrogen stream can be used in an evaporative cooling process configured to further reduce the temperature of the exhaust gas. In one or more embodiments, the exhaust gas in line **151** 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, pressurized nitrogen gas from line **151** 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**.

[0075] The combustion in combustion chamber **110** may take place under stoichiometric

or non-stoichiometric conditions. In some embodiments, stoichiometric or substantially stoichiometric combustion conditions may be desired. For example, the EGR system **124** as described herein, especially with the addition of the boost compressor **142**, can be implemented to achieve a higher concentration of CO₂ in the exhaust gas of the power generation system **100**, thereby allowing for more effective CO₂ separation for subsequent sequestration, pressure maintenance, or EOR applications. In certain embodiments disclosed herein, the concentration of CO₂ in the exhaust gas stream can be effectively increased to about 10 vol% or higher. To accomplish this, the combustion chamber **110** can be adapted to stoichiometrically combust the incoming mixture of fuel in line **112** and compressed oxidant in line **114**. In order to moderate the temperature of the stoichiometric combustion to meet expander **106** inlet temperature and component cooling requirements, a portion of the compressed recycle stream **144** can be simultaneously injected into the combustion chamber **110** as a diluent. Thus, embodiments of the disclosure may reduce or essentially eliminate any excess oxygen from the exhaust gas while simultaneously increasing its CO₂ composition. As such, the gaseous exhaust in line **122** can have less than about 3.0 vol% oxygen, or less than about 1.0 vol% oxygen, or less than about 0.1 vol% oxygen, or even less than about 0.001 vol% oxygen.

[0076] Referring now to FIG. 2, depicted is a CO₂ separation system **200** that can employ potassium carbonate (K₂CO₃) solvent technology as described herein. The CO₂ separation system **200** can be or form at least a portion of the CO₂ separator **148**, as generally described herein with reference to FIG. 1. In one or more embodiments, the system **200** can be configured to receive the purge stream **146** tapped from the compressed recycle stream **144** (FIG. 1) at a temperature of around 800 °F and a pressures of around 270 psia to about 280 psia.

[0077] The purge stream **146**, containing primarily nitrogen, CO₂, and excess combustion water, can be cooled in a heat exchanger **202**, thereby generating a cooled purge stream in line **204**. In an embodiment, the heat exchanger **202** can generate steam, which may in some cases be integrated with the steam stream **130** from the HRSG **126** (FIG. 1). Extracting CO₂ from the purge stream **146** in the CO₂ separation system **200** generates a nitrogen-rich residual stream **151** at or near the elevated pressure of the purge stream **146**. In at least one embodiment, the heat exchanger **202** can be a cross exchanger fluidly coupled to the residual stream **151** and configured to extract the heat energy associated with cooling the purge stream

146 in order to re-heat the residual stream **151**. Once reheated, the residual stream **151** can be subsequently expanded to generate mechanical power, as generally described above.

[0078] The cooled purge stream in line **204** can be directed to an absorption column **206** where a solvent from line **208** is circulated, and the residual stream **151** is simultaneously discharged overhead for further downstream processing. In one or more embodiments, the solvent is a water-based salt solution of K_2CO_3 . When compared to competing solvents, such as MEA, the K_2CO_3 solvent is quite temperature-tolerant. As a result, the cooling of the purge stream **146** can be minimized, as needed, and a higher temperature purge stream **146** can be allowed to enter the absorption column **206** without raising thermal degradation concerns. Accordingly, the degree of cooling of the purge stream **146** can be modified to match process heat requirements, rather than cooling to avoid thermal degradation.

[0079] As a result of the absorption of CO_2 by the potassium carbonate solvent in the absorption column **206**, a rich bicarbonate solvent can be discharged from the bottom of the absorption column **206** via line **210** and directed to a regeneration column **212**. In one embodiment, a first or intermediate valve **214** disposed in the line **210** can be configured to flash the bicarbonate solvent to a lower, near-atmospheric pressure before introduction to the regeneration column **212**. In at least one embodiment, the first valve **214** can be a hydraulic turbine configured to generate extra power.

[0080] The regeneration column **212** can be configured to use steam circulating therein to boil the bicarbonate solvent and reverse the reaction undertaken in the absorption column **206**, thereby yielding a regenerated, lean potassium carbonate solvent suitable for recirculation via line **216** below. In at least one embodiment, an in-line pump **218**, or the like, can drive at least a portion of the lean potassium carbonate solvent via line **220** back to the absorption column **206**.

[0081] The lean potassium carbonate solvent in line **220** can then be optionally directed through a first cooling unit **222**. In one or more embodiments, the first cooling unit **222** can be, for example, an air cooler or radiator-type heat exchanger, configured to reduce the temperature of the solvent.

[0082] In order to generate the steam circulating in the regeneration column **212** and maintain the required heat of regeneration, at least a portion of the lean potassium carbonate solvent in line **216** can be directed to a reboiler **219** via line **217**. The reboiler **219** can be

configured to increase the temperature of the lean potassium carbonate solvent in line **217**, and return a heated regenerated potassium carbonate solvent back to the regeneration column via line **221**. In at least one embodiment, the reboiler **219** can be supplied with heat from the HRSG **126** (FIG. 1). In other embodiments, however, the reboiler **219** can be supplied with
5 heat from the discharge of a backpressure type steam turbine, or from an extraction sidestream from a condensing type steam turbine.

[0083] The water included in the purge stream **146** can condense into the solvent solution in the absorption column **206**, and subsequently boil out in the regeneration column **212**. Consequently, the regeneration column **212** can further discharge CO₂ vapor and any residual
10 water via overhead line **224**. In at least one embodiment, the CO₂ vapor and residual water can be directed through a second cooling unit **226**, such as an air cooler or radiator-type heat exchanger, before being introduced into a condenser **228**. The condenser **228** can be configured to separate the residual water from any recovered CO₂ and direct the separated water into line **230** below while feeding the recovered CO₂ into line **150** overhead. As can be
15 appreciated, line **150** can be the same line **150** as described above with reference to FIG. 1. In at least one embodiment, the separated CO₂ in line **150** can be subsequently compressed for applications such as CO₂ sequestration, enhanced oil recovery, CO₂ sales, carbon capture, and/or combinations thereof.

[0084] In one embodiment, at least a portion of the separated water in line **230** can be
20 recirculated back into the regeneration column **212** via line **234** using a pump **232** to allow the balance of water in the system to be maintained. Water is constantly introduced into the solvent via stream **204**, and subsequently removed via lines **236**, **150**, and **151**. In order to maintain solvent conditions and strength, the water must remain in balance within the system **200**. Accordingly, the water recirculated in line **234** can allow water to be returned so that
25 steam raised in line **221** can be controlled independently of this water balance. In other embodiments, a portion of the residual water in line **230** can be disposed of as fresh process water via line **236**. For example, the water in line **236** can be used for irrigation water, treated to be used for boiler feed water, and/or other process water.

[0085] Referring now to FIG. 3, depicted is an illustrative embodiment of a CO₂
30 separation system **300** according to the invention, similar in some respects to the system **200** of FIG. 2 but incorporating a stripping section to remove volatiles from the rich bicarbonate solution before regeneration of the solvent. As such, the entire system **300** will not be

described in detail but may be best understood with reference to FIG. 2. As depicted in system **300** of FIG. 3, the rich bicarbonate solvent discharged from the bottom of the absorption column **206** via stream **210** can be directed to a stripping section **310**, where volatile components may be stripped from the rich bicarbonate solvent using a vapor stream **312**. The vapor stream **312** comprises a preferably clean vapor, which may be any vapor configured to remove volatile components that will not interact with CO₂. In some embodiments, the vapor stream **312** may comprise nitrogen, argon, steam, or combinations thereof. In one or more embodiments (not shown), the stripping section **310** may be incorporated as additional stages at the bottom of the absorption column **206**. In other embodiments, the stripping section **310** may be a separate column from the absorption column as shown in FIG. 3. In one or more embodiments, the stripping section **310** operates at an elevated pressure similar to that of the cooled purge stream **204**.

[0086] The stripping section **310** generates a first or overhead stream **314** comprising the stripping vapor and the volatile components stripped from the rich bicarbonate solution and a second stream **316** comprising the stripped bicarbonate solvent solution. The overhead stream **314** is recirculated to the absorption column **206**, while the bicarbonate solvent solution in line **316** is directed the regeneration column **212**. Line **316** may include a valve **318** disposed therein configured to flash the bicarbonate solvent to a lower, near-atmospheric pressure before introduction to the regeneration column **212**. In at least one embodiment, the first valve **318** can be a hydraulic turbine configured to generate extra power. Complete solvent regeneration can then take place as described above with reference to system **200**.

[0087] Referring now to FIG. 4, depicted is an illustrative embodiment of a CO₂ separation system **400** according to the invention, similar in some respects to the system **200** of FIG. 2 but incorporating a preliminary flash to an intermediate pressure to remove volatiles from the rich bicarbonate solution before regeneration of the solvent. As such, the entire system **400** will not be described in detail but may be best understood with reference to FIG. 2. As depicted in system **400** of FIG. 4, the rich bicarbonate solvent can be discharged from the bottom of the absorption column **206** via line **210** and reduced in pressure via a first valve **408** before being introduced into a flash vessel **410**. In one or more embodiments, the first valve **408** can be configured to reduce the pressure of the bicarbonate solvent from a pressure at or near that of the cooled purge stream **204** to an intermediate pressure sufficient to release volatile components such as N₂, O₂, Ar, and CO from the bicarbonate solvent while

keeping CO₂ in the liquid phase of the solution. The resulting reduced-pressure dual phase solvent solution exiting the first valve **408** may then be directed to the flash vessel **410**, where the phases are separated. The gaseous phase of the reduced-pressure solvent solution, comprising the volatile components described previously, is removed from the flash vessel **410** via volatile stream **412**, while the liquid phase of the reduced-pressure solvent solution is removed from the flash vessel via line **414** and directed to the regeneration column **212**.

[0088] In one or more embodiments, volatile stream **412** may be recycled to the exhaust gas recirculation system **124** (FIG. 1). For example, as illustrated in system **500** of FIG. 5, the volatile stream **412** may be recycled and added to the cooled recycle gas **140** before the cooled recycle gas **140** is directed to the main compressor **104**.

[0089] Referring again to the system **400** of FIG. 4, the reduced-pressure solvent solution in line **414** may be flashed to a lower, near-atmospheric pressure using a second valve **416** before being directed into the regeneration column **212**. Complete solvent regeneration can then take place as described above with reference to system **200**.

[0090] At least one benefit derived from the separation systems **300** and **400** of FIGs. 3 and 4, respectively, is the ability to produce a pure or nearly pure CO₂ stream from the regeneration column **212**. The contaminants present in the CO₂ stream in line **210** can include water and volatile gases (described above) dissolved into the circulating solvent. Because the systems of FIGs. 3 and 4 are adapted to remove essentially all of the volatile gases while keeping the CO₂ in the solution, the regeneration column **212** overhead stream **224** is left with essentially only high purity CO₂ and water. In one or more embodiments, a portion of the CO₂ in line **150** can optionally be directed into a purge line (not shown) and captured for non-EOR uses, such as chemical feedstock, food production, etc.

[0091] Certain embodiments and features have been described using a set of numerical upper limits and a set of numerical lower limits. It should be appreciated that ranges from any lower limit to any upper limit are contemplated unless otherwise indicated. All numerical values are considered to be "about" or "approximately" the stated value. Furthermore, all patents and other documents cited in this application are fully incorporated by reference to the extent such disclosure is not inconsistent with this application and for all jurisdictions in which such incorporation is permitted.

[0092] 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
5 scope of the appended claims.

CLAIMS

What is claimed is:

1. An integrated power generation system, comprising:

a gas turbine system comprising a combustion chamber configured to combust a
5 compressed oxidant and a fuel in the presence of a compressed recycle stream to generate a
discharge stream that is expanded in an expander, thereby generating a gaseous exhaust stream;

an exhaust gas recirculation system comprising a boost compressor and one or more
cooling units fluidly coupled to the boost compressor, the boost compressor being configured to
receive and increase the pressure of the gaseous exhaust stream and the one or more cooling units
10 being configured to cool the gaseous exhaust stream and provide a cooled recycle gas to the main
compressor, wherein the main compressor compresses the cooled recycle gas and generates the
compressed recycle stream;

a purge stream fluidly coupled to the compressed recycle stream having a heat exchanger
configured to reduce the temperature of the purge stream and generate a cooled purge stream;
15 and

a CO₂ separation system fluidly coupled to the heat exchanger, the CO₂ separation system
comprising:

an absorption column configured to receive the cooled purge stream and absorb
CO₂ from the cooled purge stream with a potassium carbonate solvent to generate a
20 nitrogen-rich residual stream and a bicarbonate solvent solution;

a solvent stripping section configured to receive the bicarbonate solvent solution
and strip volatile components from the bicarbonate solvent solution with a stripping
vapor; and

a regeneration column fluidly coupled to the stripping section configured to
25 receive and boil the bicarbonate solvent solution to remove CO₂ and water therefrom,
producing a regenerated potassium carbonate solvent to be recycled to the absorption
column.

2. The system of claim 1, wherein the solvent stripping section is incorporated as additional
stages in the absorption column.

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3. The system of claim 1, wherein the solvent stripping section is a column separate from the absorption column configured to generate a first stream comprising the stripping vapor and the volatile components stripped from the bicarbonate solvent solution and a second stream comprising the bicarbonate solvent solution.
- 5 4. The system of claim 3, wherein the stripping vapor comprises nitrogen, argon, steam, or a combination thereof.
5. The system of claim 1, further comprising a first valve fluidly coupled to the solvent stripping section and configured to flash the bicarbonate solvent solution to a near-atmospheric pressure before the bicarbonate solvent solution enters the regeneration column.
- 10 6. The system of claim 5, wherein the first valve is a hydraulic turbine configured to generate power.
7. The system of claim 1, further comprising a reboiler fluidly coupled to the regeneration column and configured to receive and heat a portion of the regenerated potassium carbonate solvent and produce a heated regenerated potassium carbonate solvent.
- 15 8. The system of claim 7, wherein the reboiler is configured to recycle the heated regenerated potassium carbonate solvent to the regeneration column to produce steam.
9. The system of claim 1, further comprising a condenser fluidly coupled to the regeneration column configured to receive the CO₂ and water removed from the bicarbonate solvent solution and separate the water from the CO₂.
- 20 10. The system of claim 9, wherein a portion of the water separated from the CO₂ is pumped back to the regeneration column to create steam.
11. The system of claim 1, wherein the combustion chamber is configured to stoichiometrically combust the compressed oxidant and the fuel in the presence of the compressed recycle stream.
- 25 12. The system of claim 1, wherein the compressed recycle stream acts as a diluent configured to moderate the temperature of the discharge stream.
13. An integrated power generation system, comprising:
- a gas turbine system comprising a combustion chamber configured to combust a compressed oxidant and a fuel in the presence of a compressed recycle stream to generate a
- 30 discharge stream that is expanded in an expander, thereby generating a gaseous exhaust stream;

an exhaust gas recirculation system comprising a boost compressor and one or more cooling units fluidly coupled to the boost compressor, the boost compressor being configured to receive and increase the pressure of the gaseous exhaust stream and the one or more cooling units being configured to cool the gaseous exhaust stream and provide a cooled recycle gas to the main compressor, wherein the main compressor compresses the cooled recycle gas and generates the compressed recycle stream;

a purge stream fluidly coupled to the compressed recycle stream having a heat exchanger configured to reduce the temperature of the purge stream and generate a cooled purge stream; and

a CO₂ separation system fluidly coupled to the heat exchanger, the CO₂ separation system comprising:

an absorption column configured to receive the cooled purge stream and absorb CO₂ from the cooled purge stream with a potassium carbonate solvent to generate a nitrogen-rich residual stream and a bicarbonate solvent solution;

a first valve fluidly coupled to the absorption column configured to flash the bicarbonate solvent solution to a pressure sufficient to separate volatile components from the bicarbonate solvent solution, thereby generating a dual phase reduced-pressure solvent solution having a gaseous phase comprising the volatile components and a liquid phase comprising the bicarbonate solvent solution;

a flash vessel fluidly coupled to the first valve configured to receive the reduced-pressure solvent solution and remove the gaseous phase of the reduced-pressure solvent solution from the liquid phase of the reduced-pressure solvent solution;

a second valve fluidly coupled to the flash vessel configured to receive the liquid phase of the reduced-pressure solvent solution and flash the liquid phase to a near-atmospheric pressure, thereby generating a near-atmospheric bicarbonate solvent solution; and

a regeneration column fluidly coupled to the second valve configured to receive and boil the near-atmospheric bicarbonate solvent solution to remove CO₂ and water therefrom, producing a regenerated potassium carbonate solvent to be recycled to the absorption column.

14. The system of claim 13, wherein the first valve is configured to flash the bicarbonate solvent solution to a pressure such that the gaseous phase of the bicarbonate solvent solution comprises less than 1.0 mol% carbon dioxide.

15. The system of claim 14, wherein the first valve is configured to flash the bicarbonate solvent solution to a pressure such that at least 98 mol% of the total carbon dioxide in the bicarbonate solvent solution remains in the liquid phase of the reduced-pressure solvent solution.

16. The system of claim 13, further comprising a reboiler fluidly coupled to the regeneration column and configured to receive and heat a portion of the regenerated potassium carbonate solvent and produce a heated regenerated potassium carbonate solvent.

17. The system of claim 16, wherein the reboiler is configured to recycle the heated regenerated potassium carbonate solvent to the regeneration column to produce steam.

18. The system of claim 13, further comprising a condenser fluidly coupled to the regeneration column configured to receive the CO₂ and water removed from the bicarbonate solvent solution and separate the water from the CO₂.

19. The system of claim 18, wherein a portion of the water separated from the CO₂ is pumped back to the regeneration column to create steam.

20. The system of claim 13, wherein at least a portion of the gaseous phase of the reduced-pressure solution removed from the flash vessel is recycled to the exhaust gas recirculation system.

21. The system of claim 20, wherein the at least a portion of the gaseous phase of the reduced-pressure solution recycled to the exhaust gas recirculation system is combined with the cooled recycle gas provided to the main compressor.

22. The system of claim 13, wherein the combustion chamber is configured to stoichiometrically combust the compressed oxidant and the fuel in the presence of the compressed recycle stream.

23. The system of claim 13, wherein the compressed recycle stream acts as a diluent configured to moderate the temperature of the discharge stream.

24. The system of claim 13, wherein one or both of the first and second valves is a hydraulic turbine configured to generate power.

25. A method for generating power, comprising:

combusting a compressed oxidant and a fuel in a combustion chamber and in the presence of a compressed recycle stream, thereby generating a discharge stream, and expanding the discharge stream to generate a gaseous exhaust stream;

5 increasing the pressure of the gaseous exhaust stream and cooling the gaseous exhaust stream to generate a cooled recycle gas that is compressed to generate the compressed recycle stream;

cooling a purge stream fluidly coupled to compressed recycle stream to generate a cooled purge stream;

10 directing the cooled purge stream to an absorption column and absorbing CO₂ from the cooled purge stream with a potassium carbonate solvent;

discharging a nitrogen-rich residual stream and a bicarbonate solvent solution from the absorption column;

15 stripping volatile components from the bicarbonate solvent solution with a stripping vapor;

boiling the bicarbonate solvent solution in a regeneration column to remove CO₂ and water therefrom, generating a regenerated potassium carbonate solvent; and

recycling the regenerated potassium carbonate solvent to the absorption column.

26. The method of claim 25, wherein the stripping vapor comprises nitrogen, argon, steam, or
20 a combination thereof.

27. The method of claim 25, further comprising flashing the bicarbonate solvent solution through a valve to a near-atmospheric pressure before boiling the bicarbonate solution in the regeneration column.

28. The method of claim 27, wherein the valve is a hydraulic turbine configured to generate
25 power.

29. The method of claim 25, further comprising receiving the CO₂ and water removed from the bicarbonate solvent solution in a condenser fluidly coupled to the regeneration column and separating the water from the CO₂.

30. The method of claim 29, wherein a portion of the water separated from the CO₂ in the
30 condenser is directed to the regeneration column to create steam.

31. The method of claim 25, wherein the compressed oxidant and the fuel are combusted in the presence of a compressed recycle stream under stoichiometric conditions.

32. The method of claim 25, wherein the compressed recycle stream moderates the temperature of the discharge stream.

5 33. A method for generating power, comprising:

combusting a compressed oxidant and a fuel in a combustion chamber and in the presence of a compressed recycle stream, thereby generating a discharge stream, and expanding the discharge stream to generate a gaseous exhaust stream;

10 increasing the pressure of the gaseous exhaust stream and cooling the gaseous exhaust stream to generate a cooled recycle gas that is compressed to generate the compressed recycle stream;

cooling a purge stream fluidly coupled to compressed recycle stream to generate a cooled purge stream;

15 directing the cooled purge stream to an absorption column and absorbing CO₂ from the cooled purge stream with a potassium carbonate solvent;

discharging a nitrogen-rich residual stream and a bicarbonate solvent solution from the absorption column;

20 flashing the bicarbonate solvent solution to a pressure sufficient to separate volatile components from the bicarbonate solvent solution, generating a dual phase reduced-pressure solvent solution having a gaseous phase comprising the volatile components and a liquid phase comprising the bicarbonate solvent solution;

separating the gaseous phase of the reduced-pressure solvent solution from the liquid phase of the reduced-pressure solution;

25 flashing the liquid phase of the reduced-pressure solvent solution to a near-atmospheric pressure to generate a near-atmospheric solvent solution;

boiling the near-atmospheric solvent solution in a regeneration column to remove CO₂ and water therefrom, thereby generating a regenerated potassium carbonate solvent; and

recycling the regenerated potassium carbonate solvent to the absorption column.

30 34. The method of claim 33, wherein the bicarbonate solution is flashed to a pressure such that the gaseous phase of the reduced-pressure solvent solution comprises less than 1.0 mol%

CO₂.

35. The method of claim 34, wherein the bicarbonate solution is flashed to a pressure such that at least 98 mol% of the total CO₂ in the bicarbonate solvent solution remains in the liquid phase of the reduced-pressure solvent solution.

5 36. The method of claim 33, further comprising receiving the CO₂ and water removed from the near-atmospheric solvent solution in a condenser fluidly coupled to the regeneration column and separating the water from the CO₂.

37. The method of claim 36, wherein a portion of the water separated from the CO₂ in the condenser is directed to the regeneration column to create steam.

10 38. The method of claim 33, wherein at least a portion of the gaseous phase of the reduced-pressure solvent solution is recycled and combined with the cooled recycle gas.

39. The method of claim 33, wherein the compressed oxidant and the fuel are combusted in the presence of a compressed recycle stream under stoichiometric conditions.

15 40. The method of claim 33, wherein the compressed recycle stream moderates the temperature of the discharge stream.