

LOW EMISSION POWER GENERATION SYSTEMS AND METHODS

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims the benefit of U. S. provisional patent application number
5 61/361,180, filed July 2, 2010 entitled "Low Emission Power Generation Systems and
Methods", 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
Combustion of a Fuel"; U. S. Patent Application Number 61/361,170, filed July 2, 2010
10 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
Direct Contact Cooler" and Patent Application Number 61/361,178, filed July 2, 2010,
15 entitled "Stoichiometric Combustion of Enriched Air With Exhaust Gas Recirculation".

FIELD OF THE DISCLOSURE

[0003] Embodiments of the disclosure relate to low emission power generation in
combined-cycle power systems.

BACKGROUND OF THE DISCLOSURE

20 [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
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.

25 [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
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
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 for the companies
that 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 particular, the presence of oxygen, SO_x, and NO_x components 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 Rankin cycle). However, there are no commercially available gas turbines that can operate in such a cycle and the power required to produce high purity oxygen significantly reduces the overall efficiency of the process. Several studies have compared these processes and show some of the advantages of each approach. *See, e.g.* BOLLAND, OLAV, and UNDRUM, HENRIETTE, *Removal of CO₂ from Gas Turbine Power Plants: Evaluation of pre- and post-combustion methods*, SINTEF Group, found at <http://www.energy.sintef.no/publ/xergi/98/3/3art-8-engelsk.htm> (1998).

[0007] Other approaches to lower CO₂ emissions include stoichiometric exhaust gas recirculation, such as in natural gas combined cycles (NGCC). In a conventional NGCC system, only about 40% of the air intake volume is required to provide adequate stoichiometric combustion of the fuel, while the remaining 60% of the air volume serves to moderate the temperature and cool the exhaust gas so as to be suitable for introduction into the succeeding expander. The additional air volume also disadvantageously generates excess oxygen in the exhaust, which is difficult to remove. The typical NGCC produces low pressure exhaust gas which requires a fraction of the power produced to extract the CO₂ for sequestration or 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 gas associated with the combustion of other fossil fuels, such as coal.

[0008] 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 shortcoming in the field, would benefit power generation in combined-cycle power systems.

SUMMARY OF THE DISCLOSURE

[0009] The present disclosure provides systems and methods for generating power with an integrated CO₂ separation system. Exemplary systems include a gas turbine system, an exhaust gas recirculation system, a heat exchanger, and a CO₂ separator. The gas turbine system may have a combustion chamber configured to stoichiometrically combust a

compressed oxidant and a fuel in the presence of a compressed recycle stream in order to generate a discharge stream, which is expanded in an expander, thereby generating a gaseous exhaust stream and at least partially driving a main compressor. The compressed recycle stream acts as a diluent configured to moderate the temperature of the discharge stream. The exhaust gas recirculation system may have at least one of a boost compressor and one or more cooling units configured to increase the mass flow rate of the gaseous exhaust stream to provide a cooled recycle gas to the main compressor. The main compressor compresses the cooled recycle gas and generates the compressed recycle stream, a portion of which is directed to the combustion chamber and a portion of which provides a purge stream. The CO₂ separator may be fluidly coupled to the purge stream and may comprise an absorber column, a first valve, and a regeneration column. The absorber column may be configured to receive the purge stream and circulate a potassium carbonate solvent therein to absorb CO₂ in the purge stream. The absorber column discharges a nitrogen-rich residual stream and a bicarbonate solvent solution. The first valve may be fluidly coupled to the absorber column and configured to flash the bicarbonate solvent solution to a near-atmospheric pressure. The regeneration column may be fluidly coupled to the first valve and configured to receive and boil the bicarbonate solvent solution to remove CO₂ and water therefrom, thereby producing a regenerated potassium carbonate solvent to be recirculated back to the absorber column.

[0010] The present disclosure further provides related systems and methods adapted to remove CO₂ from an exhaust gas recirculation stream.

BRIEF DESCRIPTION OF THE DRAWINGS

[0011] 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:

[0012] FIG. 1 depicts an integrated system for low emission power generation and enhanced CO₂ recovery, according to one or more embodiments of the present disclosure.

[0013] FIG. 2 depicts another integrated system for low emission power generation and enhanced CO₂ recovery, according to one or more embodiments of the present disclosure.

[0014] FIG. 3 depicts another integrated system for low emission power generation and enhanced oil recovery, according to one or more embodiments of the present disclosure.

[0015] FIG. 4 depicts an illustrative CO₂ capture system, according to one or more embodiments of the present disclosure.

[0016] FIG. 5 depicts another illustrative CO₂ capture system, according to one or more

embodiments of the present disclosure.

[0017] FIG. 6 depicts another illustrative CO₂ capture system, according to one or more embodiments of the present disclosure.

[0018] FIG. 7 depicts another illustrative CO₂ capture system, according to one or more
5 embodiments of the present disclosure.

[0019] FIG. 8 depicts an integrated system for low emission power generation and nitrogen expansion for enhanced oil recovery, according to one or more embodiments of the present disclosure.

DETAILED DESCRIPTION OF THE DISCLOSURE

10 [0020] 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
15 limited to the specific embodiments described below, but rather, it includes all alternatives, modifications, and equivalents falling within the scope of the appended claims.

[0021] 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.

20 [0022] 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 (CH₄) 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
25 (C₂H₆), higher molecular weight hydrocarbons (*e.g.*, C₃-C₂₀ 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.

[0023] As used herein, the term "stoichiometric combustion" refers to a combustion
30 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 ($CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$). 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.

[0024] Embodiments of the presently disclosed systems and processes may be used to produce ultra low emission electric power and CO_2 for enhanced oil recovery (EOR) or sequestration applications. According to embodiments disclosed herein, a mixture of air and fuel can be stoichiometrically or substantially stoichiometrically combusted and mixed with a stream of recycled exhaust gas. The stream of recycled exhaust gas, generally including products of combustion such as CO_2 , can be used as a diluent to control or otherwise moderate the temperature of the stoichiometric combustion and exhaust gas entering the succeeding expander.

[0025] By cooling the exhaust gas and condensing the water out of the stream, a relatively high content CO_2 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 CO_2 being emitted to the atmosphere.

[0026] The stoichiometric or substantially stoichiometric combustion of the fuel combined with a boost in the pressure or other increase in the mass flow rate of the exhaust gas prior to being compressed for recirculation can make the CO_2 partial pressure much higher than in conventional gas turbine exhaust. As a result, carbon capture in a CO_2 separator can be undertaken using less energy-intensive solvents, such as potassium carbonate (K_2CO_3) or sodium carbonate (Na_2CO_3). The presence of oxygen (O_2), SO_x , and 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 CO_2 content, since amine solvents can degrade in their presence. The potassium or sodium carbonate solvents tolerate the minimal oxygen content of the present disclosure without degradation. Moreover, potassium carbonate easily absorbs SO_x or NO_x , converting it to simple fertilizers such as potassium sulfite (K_2SO_3) and potassium nitrate (KNO_3). These fertilizers can be easily discharged in an environmentally harmless manner.

[0027] 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**.

[0028] 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, 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-rich air, oxygen-depleted air, pure oxygen, or combinations thereof.

[0029] 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 adapted to help facilitate the stoichiometric or substantially stoichiometric combustion of the compressed oxidant in line **114** and fuel in line **112**, and also 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**. The exhaust gas **116** is directed to the inlet of the expander **106**. 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. 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**.

[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 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 sent to the HRSG **126** in order to generate steam in 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 any variety of apparatus and/or facilities in a recycle loop back to the main compressor **104**. In the illustrated implementations, cooling units and/or booster compressors are shown and described in varying orders and configurations, each of which can be understood as being adapted to increase the mass flow rate of the cooled exhaust gas. By increasing the mass flow rate of the cooled exhaust gas entering the main compressor, a higher outlet pressure may be obtained from the main compressor.

[0032] In some implementations, and as shown in FIG. 1, the recycle loop may comprise 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 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 **138** which can, in at least one embodiment, be routed to the HRSG **126** via line **141** 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 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**.

[0033] 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 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
5 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 expander **106** power and efficiency. This can prove advantageous since the CO₂-rich exhaust gas in
10 line 116 generally maintains a higher specific heat capacity.

[0034] 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 tapped from the compressed recycle
15 stream **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 process requiring carbon dioxide, and/or compressed and injected into a terrestrial reservoir for enhanced oil recovery (EOR), sequestration, or another purpose.

[0035] A residual stream **151**, essentially depleted of CO₂ and consisting primarily of
20 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 **152**, such as a power-producing nitrogen expander, fluidly coupled to the CO₂ separator **148**. As depicted in FIGs. 1-3, 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
25 of the power generated by the gas expander **152** to drive the inlet compressor **118**. After expansion in the gas expander **152**, an exhaust gas in line **156**, consisting primarily of nitrogen, 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 as generally
30 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. In at least one embodiment, the combination of the gas expander **152**, inlet compressor **118**, and CO₂ separator can be characterized as an open Brayton cycle, or the

third power producing component of the system **100**.

[0036] In other embodiments, however, the gas expander **152** can be used to provide power to other applications, and not directly coupled to the stoichiometric 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 compressor (not shown) that demands less power. Additionally or alternatively, the expander **152** could be adapted to drive other equipment as appropriate. In yet other embodiments, as depicted in FIG. 8, the gas expander **152** can be replaced with a downstream compressor **188** configured to compress the residual stream **151** and generate a compressed exhaust gas in line **190**. In one or more embodiments, the compressed exhaust gas in line **190** 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 line **190** 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**.

[0037] 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. For instance, embodiments disclosed herein can effectively increase the concentration of CO₂ in the exhaust gas stream to about 10vol% 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 exhaust gas derived from the compressed recycle stream **144** can be injected into the combustion chamber **110** as a diluent. Thus, embodiments of the disclosure can 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 3.0vol% oxygen, or less than about 1.0vol% oxygen, or less than about 0.1vol% oxygen, or even less than about 0.001vol% oxygen.

[0038] The specifics of exemplary operation of the system **100** will now be discussed. As can 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 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 be configured as a stoichiometric compressor that provides 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.

[0039] The main compressor **104** can be configured to recycle and compress recycled exhaust gas into the compressed recycle stream **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 model of expander **106**, a ring of thermocouples and/or oxygen sensors (not shown) can be disposed associated with the combustion chamber and/or the expander. For example, thermocouples and/or oxygen sensors may be disposed on the outlet of the combustion chamber **110**, on the inlet to the expander **106** and/or on the outlet of the expander **106**. In operation, the thermocouples and sensors can be adapted to determine the compositions and/or temperatures of one or more streams for use in determining the volume of exhaust gas required as diluent to cool the products of combustion to the required expander inlet temperature. Additionally or alternatively, the thermocouples and sensors may be adapted to determine the amount of oxidant to be 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 gas in line **144** and/or compressed oxidant in line **114** can be manipulated or controlled to match the demand. The volumetric mass flow rates may be controlled through any suitable flow control systems, which may be in electrical communication with the thermocouples and/or oxygen sensors.

[0040] In at least one embodiment, a pressure drop of about 12-13 psia can be experienced across the combustion chamber **110** during 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. Because of the increased mass flow and higher specific heat capacity of the CO₂-rich exhaust gas derived from the compressed recycle stream **144**, a higher pressure

ratio can be achieved across the expander **106**, thereby allowing for higher inlet temperatures and increased expander **106** power.

[0041] The gaseous exhaust in line **122** exiting the expander **106** can have a pressure at or near ambient. In at least one embodiment, the gaseous exhaust in line **122** can have a pressure of about 15.2 psia. The temperature of the gaseous exhaust in line **122** can range from about 1180 °F to about 1250 °F before passing through the HRSG **126** to generate steam in line **130** and a cooled exhaust gas in line **132**. The cooled exhaust gas in line **132** can have a temperature ranging from about 190 °F to about 200 °F. 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 120 °F, depending primarily on wet bulb temperatures in specific locations and during specific seasons.

[0042] 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 17.1 psia to about 21 psia. Additionally or alternatively, the mass flow rate of the cooled recycle gas stream may be increased through other means, such as cooling. As a result, the main compressor **104** receives and compresses a recycled exhaust gas 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 at least one embodiment, the temperature of the compressed recycle stream **144** discharged from the main compressor **104** can be about 800 °F, with a pressure of around 280 psia.

[0043] The following table provides testing results and performance estimations based on combined-cycle gas turbines, with and without the added benefit of a boost compressor **142**, as described herein.

TABLE 1

Triple -Cycle Performance Comparison		
Power (MW)	Recirc. Cycle w/o Boost Compressor	Recirc. Cycle w/ Boost Compressor
Gas Turbine Expander Power	1055	1150
Main Compressor	538	542
Fan or Boost Compressor	13	27
Inlet Compressor	283	315
Total Compression Power	835	883
Net Gas Turbine Power	216	261
Steam Turbine Net Power	395	407

Standard Machinery Net Power	611	668
Aux. Losses	13	15
Nitrogen Expander Power	156	181
Combined Cycle Power	598	653
<i>Efficiency</i>		
Fuel Rate (mBTU/hr)	5947	6322
Heat Rate (BTU/kWh)	9949	9680
Combined Cycle Eff. (%lhv)	34.3	35.2
CO ₂ Purge Pressure (psia)	280	308

[0044] As should be apparent from Table 1, embodiments including a boost compressor 142 can result in an increase in expander 106 power (*i.e.*, "Gas Turbine Expander Power") due to the increase in pressure ratios. Although the power demand for the main compressor 104 can increase, its increase is more than offset by the increase in power output of the expander 106, thereby resulting in an overall thermodynamic performance efficiency improvement of around 1% lhv (lower heated value).

[0045] Moreover, the addition of the boost compressor 142 or cooling in the exhaust gas recirculation system can also increase the power output of the nitrogen expander 152 and the CO₂ purge pressure in the purge stream 146 line. An increase in purge pressure of the purge stream 146 can lead to improved solvent treating performance in the CO₂ separator 148 due to the higher CO₂ partial pressure. Such improvements can include, but are not limited to, a reduction in overall capital expenditures in the form of reduced equipment size for the solvent extraction process.

[0046] Referring now to FIG. 2, depicted is an alternative embodiment of the power generation system 100 of FIG. 1, embodied and described as system 200. As such, FIG. 2 may be best understood with reference to FIG. 1. Similar to the system 100 of FIG. 1, the system 200 of FIG. 2 includes a gas turbine system 102 coupled to or otherwise supported by an exhaust gas recirculation (EGR) system 124. The EGR system 124 in FIG. 2, however, can include an embodiment where the boost compressor 142 follows or may otherwise be fluidly coupled to the HRSG 126. As such, the cooled exhaust gas in line 132 can be compressed in the boost compressor 142 before being reduced in temperature in the cooling unit 134. Thus, the cooling unit 134 can serve as an aftercooler adapted to remove the heat of compression generated by the boost compressor 142. As with previously disclosed embodiments, the water dropout stream 138 may or may not be routed to the HRSG 126 to generate additional steam in line 130.

[0047] The cooled recycle gas stream **140** can then be directed to the main compressor **104** where it is further compressed, as discussed above, thereby generating the compressed recycle stream **144**. As can be appreciated, cooling the cooled exhaust gas in line **132** in the cooling unit **134** after compression in the boost compressor **142** can reduce the amount of power required to compress the cooled recycle gas stream **140** to a predetermined pressure in the succeeding main compressor **104**.

[0048] FIG. 3 depicts another embodiment of the low emission power generation system **100** of FIG. 1, embodied as system **300**. As such, FIG. 3 may be best understood with reference to FIGs. 1 and 2. Similar to the systems **100**, **200** described in FIGs. 1 and 2, respectively, the system **300** includes a gas turbine system **102** supported by or otherwise coupled to an EGR system **124**. The EGR system **124** in FIG. 3, however, can include a first cooling unit **134** and a second cooling unit **136**, having the boost compressor **142** fluidly coupled therebetween. As with previous embodiments, each cooling unit **134**, **136** can be a direct contact cooler, trim cooler, or the like, as known in the art.

[0049] In one or more embodiments, the cooled exhaust gas in line **132** discharged from the HRSG **126** can be sent to the first cooling unit **134** to produce a condensed water dropout stream **138** and a cooled recycle gas stream **140**. The cooled recycle gas stream **140** can be directed to the boost compressor **142** in order to boost the pressure of the cooled recycle gas stream **140**, and then direct it to the second cooling unit **136**. The second cooling unit **136** can serve as an aftercooler adapted to remove the heat of compression generated by the boost compressor **142**, and also remove additional condensed water via a water dropout stream **143**. In one or more embodiments, each water dropout stream **138**, **143** may or may not be routed to the HRSG **126** to generate additional steam in line **130**.

[0050] The cooled recycle gas stream **140** can then be introduced into the main compressor **104** to generate the compressed recycle stream **144** nominally above or at the combustion chamber **110** pressure. As can be appreciated, cooling the cooled exhaust gas in line **132** in the first cooling unit **134** can reduce the amount of power required to compress the cooled recycle gas stream **140** in the boost compressor **142**. Moreover, further cooling exhaust in the second cooling unit **136** can reduce the amount of power required to compress the cooled recycle gas stream **140** to a predetermined pressure in the succeeding main compressor **104**.

[0051] The combination of stoichiometric combustion in the combustion chamber **110** and water removal through the cooling units **134**, **136**, allows the CO₂ content in the exhaust gas (e.g., streams **122**, **132**, **140**, and/or **144**) to accumulate to about 10vol% or higher, which

is higher than exhaust gases in conventional combined-cycle systems. These effects, plus the impact of higher mass flow rates resulting from the implementation and effect of the boost compressor **142** and/or cooling units, make the CO₂ partial pressure much higher than conventional gas turbine exhaust. Consequently, this allows for carbon capture in the CO₂ separator **148** using less energy-intensive solvents, such as potassium carbonate (K₂CO₃) solvent technology.

[0052] The presence of oxygen (O₂), SO_x, and NO_x 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 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 **110** is intended to be stoichiometric, a fraction of oxygen may nonetheless be present in the purge stream **146** due to combustion equilibrium limitations. While the use of MEA solvents in this application would require significant solvent reclamation and complicated disposal, the use of potassium carbonate solvents eliminates oxygen-based solvent degradation.

[0053] 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 potassium sulfite and potassium nitrate 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.

[0054] Referring to FIG. 4, depicted is an exemplary embodiment of a CO₂ separation system **400** that can employ potassium carbonate solvent technology as described herein. The CO₂ separation system **400** can be or form at least a portion of the CO₂ separator **148**, as generally described herein with reference to FIGs. 1-3. In one or more embodiments, the system **400** can be configured to receive the purge stream **146** tapped from the compressed recycle stream **144** (FIGs. 1-3) at a temperature of around 800 °F and a pressures of around 270 psia to about 280 psia.

[0055] The purge stream **146**, containing primarily nitrogen, CO₂, and excess combustion water, can be cooled in a heat exchanger **402** to a temperature ranging from about 250 °F to about 300 °F, thereby generating a cooled purge stream in line **404**. In an embodiment, the heat exchanger **402** can generate steam to be integrated with the steam stream **130** from the HRSG **126** (FIGs. 1-3). Extracting CO₂ from the purge stream **146** in the CO₂ separation system **400** generates a nitrogen-rich residual stream **151** at or near the elevated pressure of the purge stream **146** and at a temperature of about 150 °F. In at least one embodiment, the heat exchanger **402** can be a cross-exchange heat 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**, consisting primarily of a nitrogen vapor having a temperature of about 750 °F and a pressure of around 270-280 psia, can be subsequently expanded to generate mechanical power, as generally described above.

[0056] The cooled purge stream in line **404** can be directed to an absorber column **406** where a solvent from line **408** is circulated, and the residual stream **151** is simultaneously discharged overhead for further downstream processing. In one embodiment, the solvent is a water-based salt solution of potassium carbonate. When compared to competing solvents, such as MEA, the potassium carbonate 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 absorber column **406** 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.

[0057] As CO₂ is absorbed by the potassium carbonate in the absorber column **406**, 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:



[0058] As a result, a rich, bicarbonate solvent can be discharged from the bottom of the absorber column **406** via line **410** and directed to a regeneration column **412**. In one embodiment, a first or intermediate valve **414** disposed in the line **410** can be configured to flash the bicarbonate solvent to a lower, near-atmospheric pressure before introduction to the regeneration column **412**. In at least one embodiment, the first valve **414** can be a hydraulic turbine configured to generate extra power.

[0059] In at least one embodiment, the regeneration column **412** can operate at temperatures exceeding the normal boiling point of water. For example, the regeneration column **412** can operate at a temperature range from about 220 °F, about 230 °F, or about 240 °F to about 280 °F, about 290 °F, or about 300 °F. The regeneration column **412** can operate at pressures ranging from about 0 psig to about 10 psig. In at least one embodiment, the regeneration column **412** can be configured to operate at a pressure of about 3 psig. The regeneration column **412** can be configured to use steam circulating therein to boil the bicarbonate solvent and reverse the reaction undertaken in the absorber column **406**, thereby yielding a regenerated, lean potassium carbonate solvent suitable for recirculation via line **416** below. In at least one embodiment, an in-line pump **418**, or the like, can drive at least a portion of the lean potassium carbonate solvent via line **420** back to the absorber column **406**.

[0060] En route to the absorber column **406**, a portion of the lean potassium carbonate solvent can be removed as a heat stable salt (HSS) via line **423**. As described above, illustrative HSSs extracted via line **423** can include compound fertilizers such as, but not limited to, potassium sulfite and/or potassium nitrate. In order to make up for the loss of potassium carbonate content removed via line **423**, and to maintain overall solution strength, a stream of potassium hydroxide can be subsequently added via line **425**. In one or more embodiments, the potassium hydroxide serves as a solvent makeup. The lean potassium carbonate solvent in line **420** can then be optionally directed through a first cooling unit **422**. In one or more embodiments, the first cooling unit **422** 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 **422** can be configured to reduce the temperature of the lean potassium carbonate solvent to temperatures ranging between about 230 °F and about 60 °F. As can be appreciated, in at least one embodiment the HSSs can alternatively be removed as fertilizers subsequent to the first cooling unit **422**, as well as the addition of potassium hydroxide.

[0061] In order to generate the steam circulating in the regeneration column **412** and maintain the required heat of regeneration, at least a portion of the lean potassium carbonate solvent in line **416** can be directed to a reboiler **419** via line **417**. The reboiler **419** can be configured to increase the temperature of the lean potassium carbonate solvent in line **417**, and return a heated regenerated potassium carbonate solvent back to the regeneration column via line **421**. In at least one embodiment, the reboiler **419** can be supplied with heat from the HRSG **126** (FIGs. 1-3). In other embodiments, however, the reboiler **419** can be supplied with heat from the discharge of the steam gas turbine **128** (FIGs. 1-3).

[0062] The water included in the purge stream **146** can condense into the solvent solution

in the absorber column **406**, and subsequently boil out in the regeneration column **412**. Consequently, the regeneration column **412** can further discharge CO₂ vapor and any residual water via overhead line **424**. In at least one embodiment, the CO₂ vapor and residual water can be directed through a second cooling unit **426**, such as an air cooler or radiator-type heat exchanger, before being introduced into a condenser **428**. The condenser **428** can be configured to separate the residual water from any recovered CO₂ and direct the separated water into line **430** below while feeding the recovered CO₂ into line **150** overhead. As can be appreciated, line **150** can be the same line **150** as described above with reference to FIGs. 1-3. 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.

[0063] In one embodiment, at least a portion of the separated water in line **430** can be recirculated back into the regeneration column **412** via line **434** using a pump **432** to allow the balance of water in the system to be maintained constant. Water is constantly introduced into the solvent via stream **404**, and subsequently removed via lines **436**, **150**, and **151**. In order to maintain solvent conditions and strength, the water must remain in balance within the system **400**. Accordingly, the water recirculated in line **434** can allow water to be returned so that steam raised in line **421** can be controlled independently of this water balance. In other words, this recirculated water can be used as feedwater for the generation of steam in the regeneration column **412** or to raise low pressure steam from feed cooling. In other embodiments, a portion of the residual water in line **430** can be disposed of as fresh process water via line **436**. For example, although containing a portion of dissolved CO₂, the water in line **436** can be used for irrigation water, treated to be used for boiler feed water, and/or other process water.

[0064] Referring now to FIG. 5, depicted is another illustrative embodiment of a CO₂ separation system **500**, similar in some respects to the system **400** of FIG. 4. As such, the entire system **500** will not be described in detail but may be best understood with reference to FIG. 4. Whereas the system **400** of FIG. 4 could be characterized as a single-stage potassium carbonate process, the system **500** of FIG. 5 can be characterized, in at least one embodiment, as a two-stage potassium carbonate process. As depicted, the CO₂ separation system **500** can include a "semi-lean" solvent recirculation loop, wherein a portion of the solvent can be withdrawn from the regeneration column **412** via line **502** prior to complete regeneration. In at least one embodiment, the portion of the solvent withdrawn via line **502** can be about 50% or more of the total solvent volume circulating through the regeneration column **412**. The

balance of the solvent solution remaining in the regeneration column **412** can be fully regenerated, as described above, and discharged via line **416** therebelow.

[0065] A pump **504** disposed within line **502** can direct the semi-lean solvent solution to the absorber column **406**. In one embodiment, the semi-lean solvent solution can be fed low
5 **506** into the absorber column **406**. Being only partially regenerated, the semi-lean solvent in line **502** is not able to absorb CO₂ from the lower concentration gases higher in the absorber column **406**. Instead, it can be fed into the absorber column **406** where it can absorb the maximum amount of CO₂, and not dilute the fully lean solvent entering the absorber column **406** via line **408**.

10 [0066] This variation in the system **500** can require a higher solvent circulation flowrate than the system **400** of FIG. 4, but can demand less external heat energy to remove the CO₂. With this improved thermal efficiency, the system **500** can require less reboiler **419** heat duty than is contained in the purge stream **146**. In other words, the heat of the incoming purge stream **146** may be able to supply all the reboiler **419** heat requirements. Consequently, if the
15 residual stream **151** is injected for EOR, the system **500** can be thermally self-sufficient and require no make-up heat from the power turbine HRSG **126**.

[0067] Referring now to FIG. 6, depicted is another exemplary embodiment of a CO₂ separation system **600**, similar in some respects to the systems **400**, **500** of FIGs. 4 and 5, respectively. As such, the entire system **600** will not be described in detail but may be best
20 understood with reference to FIGs. 4 and 5. As depicted, the rich, bicarbonate solvent can be discharged from the bottom of the absorber column **406** via line **410** and reduced in pressure using a first valve **602** before being introduced into a separator **604**. In one embodiment, the first valve **602** can be configured to reduce the pressure of the bicarbonate solvent from the purge stream **146** pressure (*e.g.*, between about 270 – 280 psia) to an intermediate pressure
25 level. In one or more embodiments, the intermediate pressure level can range from about 20 psia to about 50 psia.

[0068] The separator **604** can be configured to receive the reduced-pressure solution and remove at least a portion of CO₂ via overhead line **606**. In one or more embodiments, the removed CO₂ in line **606** can be cooled in a cooling unit **608**, and subsequently fed into a
30 downstream compression system **607**. In one or more embodiments, the cooling unit **608** can be a direct contact cooler, trim cooler, a mechanical refrigeration unit, or combinations thereof. Since the removed portion of CO₂ in line **606** is at an elevated pressure, albeit an intermediate pressure between the pressure of the purge stream **146** and atmospheric, it can be injected into an intermediate stage of the downstream compression system **607**, thereby

reducing the required compression load on the compression system **607**.

[0069] The balance of the CO₂ and bicarbonate solvent remaining in the separator **604** can be discharged from the separator **604** via line **610** below and flashed to a lower, near-atmospheric pressure in stream **611** using a second valve **612** before being directed into the regeneration column **412**. In several embodiments of the system **600**, complete solvent regeneration can then take place as described above with reference to either system **400** or system **500** as depicted in FIGs. 4 or 5, respectively. For instance, as described above a separated portion of CO₂ can be extracted from the condenser **428** via line **150** at or near atmospheric pressure and directed to a first compression stage of the downstream compression system **607**. Consequently, the downstream compression system **607** can receive at least two feed streams substantially including captured CO₂; one feed stream having high pressure CO₂ in line **606** that is injected into an intermediate compression stage, and a second feed stream having low pressure CO₂ in line **150** and injected at the first compression stage. As can be appreciated, such an arrangement can reduce the power demand for CO₂ compression in preparation for EOR or sequestration at virtually no increase in regenerator column **412** thermal load.

[0070] At least one benefit derived from the system **600** is the ability to produce a pure or nearly pure CO₂ stream from the regeneration column **412**. The contaminants present in the CO₂ stream in line **410** can include water and some volatile gases (*e.g.*, N₂, CO, Ar, etc.) dissolved into the circulating solvent. The system **600** can be adapted to remove essentially all of these volatile gases, leaving the regeneration column **412** overhead stream **424** with only high purity CO₂ and water. In one or more embodiments, the CO₂ concentration in the overhead line **424** can be around 2/3 of the total CO₂ flow in the system **600**. Once separated from the water, a portion of the CO₂ in line **150** can be directed into a purge line **614** and captured for non-EOR uses, such as chemical feedstock, food production, etc.

[0071] As can be appreciated, embodiments and features disclosed with reference to FIGs. 5-6 can be combined without departing from the disclosure. Accordingly, the following table and supplemental information provides illustrative process data for a combination of embodiments and/or features described above. The solvent stream and gas stream reference numerals shown in the table can be referred to in FIGs. 5-6.

TABLE 2 – Process Data

<u>Solvent Stream Number</u>	<u>408</u>	<u>506</u>	<u>410</u>	<u>611</u>	<u>434</u>
Temperature - °F	120	219.81	230.8	208.3	112
Pressure - psia	276.2	277.2	276.2	17.7	16.7
Flowrate (klb/hr)	5,079	14,036	19,988	19,701	220
Flowrate (USGPM)	8,937	23,757	33,795	650,017	443
Equiv. wt % K ₂ CO ₃ in solution	35.60%	31.80%	31.40%	31.80%	0.00%
% K ₂ CO ₃ reacted to KHCO ₃	7.80%	33.50%	65.60%	54.70%	N / A
Stream pH	9.6	8.6	8.1	8.5	4.1
<u>Gas Stream Number</u>	<u>146</u>	<u>151</u>	<u>606</u>	<u>424</u>	
Temperature - °F	803.2	141.62	120	112	
Pressure - psia	283.2	276.2	28	16.7	
Flowrate (lbmole/hr)	158,729	132,137	5,497	10,969	
Flowrate (MMSCFD)	1,446	1,203	50	100	
H ₂ O Mole %	7.97%	0.98%	6.14%	8.17%	
CO ₂ Mole %	10.36%	1.00%	91.69%	91.83%	
Mole % Other (N ₂ +O ₂ +Ar+CO+H ₂)	81.67%	98.02%	2.17%	0.00%	

Heat Required:

Feed Gas Cross-exchanger 402	629 MBTU/hr	<u>Total:</u>
Regenerator Reboiler 419	586 MBTU/hr (20 psig steam)	586 MBTU/hr

Heat Rejected:

Cooling Unit 608	114 MBTU/hr	
Condenser 428	381 MBTU/hr	
Cooling Unit 422	478 MBTU/hr	<u>Total:</u>
CO ₂ Compressor Coolers (total)	216 MBTU/hr	1189 MBTU/hr

Power Loads:

Gas Expander 152 (FIGs. 1-3)	222,414 hp	Produced	
Lean Solvent Pump 418	2,035 hp	Consumed	
Semi-Lean Solvent Pump 504	5,532 hp	Consumed	
CO ₂ Compressor (total)	49,450 hp	Consumed	<u>Total:</u>
Net Power Produced/Consumed	165,397 hp	Consumed	165,397hp

[0072] Referring now to FIG. 7, depicted is another exemplary embodiment of a CO₂ separation system **700**. Since the system **700** is similar in some respects to the systems **400** and **500** described above, the entire system **700** will not be described in detail but may be best understood with reference to FIGs. 4 and 5. The system **700** can prove particularly advantageous in embodiments where the residual stream **151** and captured CO₂ in line **150** are to be reinjected in EOR applications. As will be described below, the system **700** can be

configured to allow superior integration of the cooling of purge stream **146** in conjunction with the process heat requirements in the regeneration column **412** and reboiler **419**.

[0073] Since the residual stream **151** in the system **700** may be subsequently compressed for EOR, the heat exchanger **402** is not necessarily cross-exchanged with the residual stream **151**, but instead its heat energy can be available for other uses. For example, in one or more embodiments, the heat exchanger **402** can be configured to receive at least a portion of the recovered combustion water, or wastewater from line **436** to generate a low pressure steam in line **702**. The resulting steam in line **702** can have a pressure of about 50 psig or higher and can be split into lines **702a** and **702b** and used as motive power gas for one or more eductors **704a** and **704b**. While two lines **702a** and **702b** and two eductors **704a** and **704b** are shown in FIG. 7, it will be appreciated that there can be more or less, without departing from the scope of the disclosure.

[0074] In one embodiment, the eductors **704a** and **704b** can be configured as steam ejectors adapted to reduce the pressure on the lean potassium carbonate solvent discharged into line **416** from the regeneration column **412**. To accomplish this, the lean solvent in line **416** can be directed into one or more mixing chambers **706a** and **706b** arranged in series and fluidly coupled to the eductors **704a** and **704b**, respectively. In one embodiment, the first mixing chamber **706a** can feed the second mixing chamber **706b** for further processing. In other embodiments, however, the mixing chambers **706a** and **706b** may be arranged in parallel, without departing from the scope of the disclosure.

[0075] In operation, the eductors **704a** and **704b** can be adapted to accelerate the steam in line **702** to create a low-pressure zone at or near vacuum conditions configured to flash-boil the lean solvent in the mixing chambers **706a** and **706b**. Boiling the lean solvent can release additional water and CO₂ not recovered via overhead line **424** and draw the resulting gaseous effluent into lines **708a** and **708b**. The resulting effluent in lines **708a** and **708b**, can be injected into the regeneration column **412** to remove and capture the excess CO₂ via overhead line **424**. Because of its steam content, the effluent can also serve as stripping steam, thereby supplementing or entirely replacing at least some of the regenerative boiling heat duty generally supplied by the reboiler **419**. Accordingly, the system **700** can allow some of the heat held in the lean solvent to drive the vapor flow in the mixing chambers **706a** and **706b**, thereby reducing the net heat required for solvent regeneration and the overall size of the reboiler **419**.

[0076] Flash-boiling the additional water and CO₂ in the mixing chambers **706a** and **706b** can also simultaneously cool the remaining lean solvent by reducing its pressure from about 3

psig to about 10 psig vacuum. In one or more embodiments, the temperature of the lean solvent can be reduced from about 240 °F, about 230 °F, or about 220 °F to about 210 °F, about 200 °F, or about 190 °F. The cooled lean solvent can then be discharged from the mixing chamber **706b** via line **710** and then directed to the in-line pump **418** which, as described above, can drive the solvent via line **420** back to the absorber column **406**. Since the temperature of the lean solvent can be cooled in the mixing chambers **706a** and **706b**, the size of the cooling unit **422** can be reduced.

[0077] Because the low pressure steam provided in lines **702a** and **702b** to eductors **704a** and **704b**, respectively, is injected into the regeneration column **412**, it can result in the consumption of at least a portion of the feedwater derived from the separated water in line **434**. Accordingly, any additional water can be recovered from the regeneration column **412** via the overhead line **424** as additional wastewater. As a result, excess water can be continually building up in the system **700** and may be extracted via the wastewater line **436**. As can be appreciated, the water reflux rate can be varied to maintain the solvent water balance, or the potassium carbonate solution strength.

[0078] As can be appreciated, embodiments and features disclosed with reference to FIGs. 5-7 can be combined without departing from the disclosure. Accordingly, the following table and supplemental information provides illustrative process data for an exemplary combination of embodiments and/or features described above. The solvent stream and gas stream reference numerals shown in the table can be referred to in FIGs. 5-7.

TABLE 3 – Process Data

<u>Solvent Stream Number</u>	<u>408</u>	<u>506</u>	<u>410</u>	<u>611</u>	<u>416</u>	<u>710</u>	<u>434</u>
Temperature - °F	126	225.7	239.1	212	227.7	192.5	112
Pressure - psia	276.2	277.2	276.2	17.7	17.7	8.7	16.7
Flowrate (klb/hr)	4,966	11,380	17,210	16,866	5,142	4,966	64
Flowrate (USGPM)	8,749	20,267	29,088	642,184	8,643	8,219	129
Equiv. wt % K ₂ CO ₃ in solution	35.10%	32.80%	31.80%	32.50%	33.90%	35.10%	0.00%
% K ₂ CO ₃ reacted to KHCO ₃	5.20%	20.50%	63.70%	51.20%	5.90%	5.20%	N / A
Stream pH	9.7	8.9	8.1	8.5	9.4	9.5	4.1
<u>Gas Stream Number</u>	<u>436</u>	<u>151</u>	<u>606</u>	<u>150</u>	<u>708a,b</u>	<u>702a,b</u>	
Temperature - °F	803.2	152.6	126	112	286.6	297.8	
Pressure - psia	283.2	276.2	28	16.7	17.7	64.7	
Flowrate (lbmole/hr)	158,729	132,582	5,387	11,114	34,169	24,457	
Flowrate (MMSCFD)	1,446	1,208	49	101	311	223	
H ₂ O Mole %	7.97%	1.30%	7.24%	8.17%	99.86%	100%	

CO ₂ Mole %	10.36%	1.00%	90.83%	91.83%	0.14%	0%	
Mole % Other (N ₂ +O ₂ +Ar+CO+H ₂)	81.67%	97.70%	1.93%	0.00%	0.00%	0%	

Heat Required: None (feed gas supplies all heat)

Heat Rejected:

Cooling Unit **608** 139 MBTU/hr

Condenser **428** 611 MBTU/hr

Cooling Unit **422** 271 MBTU/hr

CO₂ Compressor Coolers
(total)

217 MBTU/hr

Total:

1,273 MBTU/hr

Power Loads:

Lean Solvent Pump **418** 2,047 hp Consumed

Semi-Lean Solvent Pump
504

4,473 hp Consumed

Total:

55,992

CO₂ Compressor (total)

49,473 hp Consumed

hp

Material Export

Inert Gas (primarily N₂) 151 1,208 Mscfd @ 276.2 psia

[0079] 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. An integrated CO₂ separation system, comprising:

a gas turbine system having a combustion chamber configured to stoichiometrically combust a compressed oxidant and a fuel in the presence of a compressed recycle stream in order to generate a discharge stream, which is expanded in an expander, thereby generating a gaseous exhaust stream and at least partially driving a main compressor, wherein the compressed recycle stream acts as a diluent configured to moderate the temperature of the discharge stream;

an exhaust gas recirculation system having at least one of a boost compressor and one or more cooling units configured to increase the mass flow rate of the gaseous exhaust stream to 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 portion of which is directed to the combustion chamber and a portion of which provides a purge stream;

and

a CO₂ separator fluidly coupled to the purge stream, the CO₂ separator comprising:

an absorber column configured to receive the purge stream and circulate a potassium carbonate solvent therein to absorb CO₂ in the purge stream, wherein the absorber column discharges a nitrogen-rich residual stream and a bicarbonate solvent solution;

a first valve fluidly coupled to the absorber column and configured to flash the bicarbonate solvent solution to a near-atmospheric pressure; and

a regeneration column fluidly coupled to the first valve and configured to receive and boil the bicarbonate solvent solution to remove CO₂ and water therefrom, thereby producing a regenerated potassium carbonate solvent to be recirculated back to the absorber column.

2. The system of claim 1, wherein the temperature of the purge stream is about 800 °F, and the pressure of the purge stream is about 280 psia.

3. The system of claim 2, further comprising a heat exchanger associated with the purge stream, wherein the heat exchanger is a cross-exchange heat exchanger configured to reduce the temperature of the purge stream to between about 250 °F and about 300 °F.

4. The system of claim 1, wherein the regeneration column operates at a pressure of about 3 psig.

5. 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.

6. The system of claim 5, wherein the reboiler is configured to recirculate the heated regenerated potassium carbonate solvent back into the regeneration column to produce steam for boiling the bicarbonate solvent solution.

7. The system of claim 1, further comprising a condenser fluidly coupled to the regeneration column and configured to receive and separate the CO₂ and water removed from the bicarbonate solvent solution, wherein the CO₂ is directed to a downstream compression system.

8. The system of claim 7, wherein a portion of the water separated from the CO₂ is pumped back into the regeneration column to create steam.

9. The system of claim 1, wherein a portion of the bicarbonate solvent solution is withdrawn from the regeneration column prior to complete solvent regeneration, and recirculated and fed low into the absorber column.

10. The system of claim 9, wherein about 50% or more of a total amount of bicarbonate solvent solution is withdrawn from the regeneration column prior to complete solvent regeneration.

11. An integrated CO₂ separation system, comprising:

a gas turbine system having a combustion chamber configured to stoichiometrically combust a compressed oxidant and a fuel in the presence of a compressed recycle stream in order to expand a discharge stream in an expander, thereby generating a gaseous exhaust stream and at least partially driving a main compressor, wherein the compressed recycle stream acts as a diluent configured to moderate the temperature of the discharge stream;

an exhaust gas recirculation system having a boost compressor and one or more cooling units fluidly coupled to the boost compressor, the boost compressor being configured to receive and boost 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 and having a heat exchanger configured to reduce the temperature of the purge stream and generate a cooled purge stream; and

a CO₂ separator fluidly coupled to the heat exchanger, the CO₂ separator comprising:

an absorber column configured to receive the cooled purge stream and circulate a potassium carbonate solvent therein to absorb CO₂ in the cooled purge stream, wherein the absorber column discharges a nitrogen-rich residual stream and a bicarbonate solvent solution;

a first valve fluidly coupled to the absorber column and configured to flash the bicarbonate solvent solution to a lower pressure, thereby generating a reduced-pressure solution;

a separator fluidly coupled to the first valve and configured to receive the reduced-pressure solution and remove a first portion of CO₂ therefrom to be injected into an inner stage of a downstream compression system;

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

a regeneration column fluidly coupled to the second valve and configured to receive and boil the near-atmospheric bicarbonate solvent solution to remove a second portion of CO₂ and water, thereby producing a regenerated potassium carbonate solvent to be recirculated back to the absorber column.

12. The system of claim 11, wherein the temperature of the purge stream is about 800 °F, and the pressure of the purge stream is about 280 psia.

13. The system of claim 12, wherein the heat exchanger is a cross-exchange heat exchanger configured to reduce the temperature of the purge stream to between about 250 °F and about 300 °F.

14. The system of claim 13, further comprising a high pressure cooling unit configured to cool the first portion of CO₂ prior to injection into the inner stage of the downstream compression system.

15. The system of claim 13, further comprising a condenser fluidly coupled to the regeneration column and configured to separate the second portion of CO₂ from the water and direct the second portion of CO₂ to a first stage of the downstream compression system.

16. A method of separating CO₂, comprising:

stoichiometrically 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 to be expanded in an expander that drives a main compressor and generates a gaseous exhaust stream, wherein the compressed recycle stream moderates the temperature of the discharge stream;

increasing the pressure of the gaseous exhaust stream with a boost compressor and cooling the gaseous exhaust stream with one or more cooling units fluidly coupled to the boost compressor, whereby a cooled recycle gas is directed into the main compressor for compression, wherein the main compressor compresses the cooled recycle gas to generate the compressed recycle stream;

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

directing the cooled purge stream into an absorber column having a potassium carbonate solvent circulating therein, the potassium carbonate solvent being configured to absorb CO₂ present in the cooled purge stream;

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

flashing the bicarbonate solvent solution to a near-atmospheric pressure through a valve;

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

recirculating the regenerated potassium carbonate solvent back to the absorber column.

17. The method of claim 16, further comprising increasing the temperature of a portion of the regenerated potassium carbonate solvent in a reboiler to produce a heated regenerated potassium carbonate solvent.

18. The method of claim 17, further comprising recirculating the heated regenerated potassium carbonate solvent back into the regeneration column to produce steam for boiling the bicarbonate solvent solution.

19. The method of claim 16, further comprising separating the CO₂ from the water removed from the bicarbonate solvent solution in a condenser fluidly coupled to the regeneration column, and directing the CO₂ to a downstream compression system.

20. The method of claim 19, directing a portion of the water separated from the CO₂ in the separated back into the regeneration column to create steam.

21. The method of claim 16, further comprising withdrawing a portion of the bicarbonate solvent solution from the regeneration column prior to complete solvent regeneration, and feeding the withdrawn bicarbonate solvent solution low into the absorber column.

22. An integrated CO₂ separation system, comprising:

5 a gas turbine system having a combustion chamber configured to stoichiometrically combust a compressed oxidant and a fuel in the presence of a compressed recycle stream in order to expand a discharge stream in an expander, thereby generating a gaseous exhaust stream and at least partially driving a main compressor, wherein the compressed recycle stream acts as a diluent configured to moderate the temperature of the discharge stream;

10 an exhaust gas recirculation system having a boost compressor and one or more cooling units fluidly coupled to the boost compressor, the boost compressor being configured to receive and boost 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
15 generates the compressed recycle stream;

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

a CO₂ separator fluidly coupled to the heat exchanger, the CO₂ separator comprising:

20 an absorber column configured to receive the cooled purge stream and circulate a potassium carbonate solvent therein to absorb CO₂ in the cooled purge stream, wherein the absorber column discharges a nitrogen-rich residual stream and a bicarbonate solvent solution;

25 a valve fluidly coupled to the absorber column and configured to flash the bicarbonate solvent solution to a near-atmospheric pressure;

a regeneration column fluidly coupled to the valve and configured to receive and boil the bicarbonate solvent solution to remove a first portion of CO₂ and water therefrom, thereby producing a regenerated potassium carbonate solvent;

30 one or more mixing chambers fluidly coupled to the regeneration column and corresponding one or more eductors, the one or more mixing chambers being configured to receive the regenerated potassium carbonate solvent, and the one or more eductors being configured to receive the low pressure steam from the heat exchanger and flash-boil the regenerated potassium carbonate solvent to extract a

second portion of CO₂ and water to be recirculated back to the regeneration column; and

a pump fluidly coupled to at least one of the one or more mixing chambers and configured to direct a remaining portion of regenerated potassium carbonate solvent back to the absorber column.

23. The system of claim 22, wherein the low pressure steam has a pressure of about 50 psig or higher.

24. The system of claim 22, further comprising a condenser fluidly coupled to the regeneration column and configured to separate the first portion of CO₂ from the water removed from the regeneration column and direct the first portion of CO₂ to a downstream compression system.

25. The system of claim 24, wherein a first portion of the water separated from the CO₂ is pumped back into the regeneration column to create steam.

26. The system of claim 25, wherein a second portion of the water separated from the CO₂ is directed to the heat exchanger to generate the low pressure steam.

27. The system of claim 22, 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 to be recirculated back into the regeneration column to produce steam for boiling the bicarbonate solvent solution.

28. A method of separating CO₂, comprising:

stoichiometrically 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 to be expanded in an expander that drives a main compressor and generates a gaseous exhaust stream, wherein the compressed recycle stream moderates the temperature of the discharge stream;

increasing the pressure of the gaseous exhaust stream with a boost compressor and cooling the gaseous exhaust stream with one or more cooling units fluidly coupled to the boost compressor, whereby a cooled recycle gas is directed into the main compressor for compression, wherein the main compressor compresses the cooled recycle gas to generate the compressed recycle stream;

cooling a purge stream fluidly coupled to compressed recycle stream with a heat exchanger to generate a cooled purge stream and a low pressure steam;

directing the cooled purge stream into an absorber column having a potassium carbonate solvent circulating therein, the potassium carbonate solvent being configured to absorb CO₂ present in the cooled purge stream;

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

flashing the bicarbonate solvent solution to a near-atmospheric pressure through a valve;

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

injecting the low pressure steam into one or more eductors fluidly coupled to one or more mixing chambers, wherein the one or more mixing chambers are configured to receive the regenerated potassium carbonate solvent;

15 flash-boiling the regenerated potassium carbonate solvent from the regeneration column in one or more mixing chambers fluidly coupled to one or more eductors to produce an effluent comprising a second portion of CO₂ and water;

accelerating the low pressure steam through the one or more eductors to extract the effluent from the one or more mixing chambers, wherein the effluent is recirculated back to the regeneration column;

20 recirculating a remaining portion of regenerated potassium carbonate solvent back to the absorber column.

29. The method of claim 28, further comprising separating the first portion of CO₂ from the water removed from the bicarbonate solvent solution in a condenser fluidly coupled to the regeneration column, and directing the CO₂ to a downstream compression system.

25 30. The method of claim 29, further comprising directing a first portion of the water separated from the CO₂ in the condenser back into the regeneration column to create steam.

31. The method of claim 30, further comprising directing a second portion of the water separated from the CO₂ in the condenser to the heat exchanger to generate the low pressure steam.

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