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(54) **STAGED CHEMICAL LOOPING PROCESS WITH INTEGRATED OXYGEN GENERATION**

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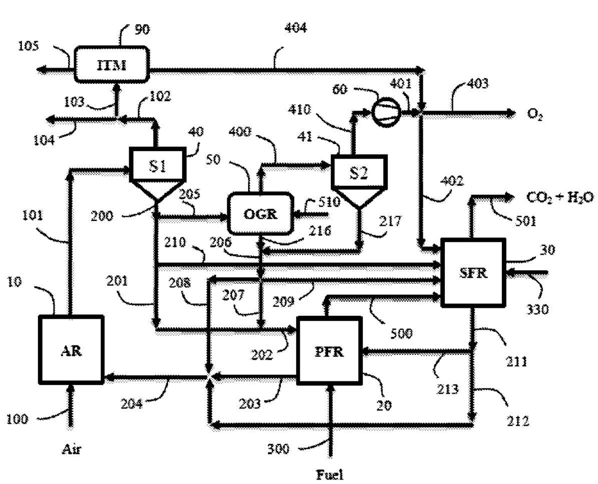
(57) **ABSTRACT**

Disclosed is a method for enhanced fuel combustion to maximize the capture of by-product carbon dioxide. According to various embodiments of the invention, a method for combusting fuel in a two-stage process is provided, which includes in-situ oxygen generation. In-situ oxygen generation allows for the operation of a second oxidation stage to further combust fuel, thus maximizing fuel conversion efficiency. The integrated oxygen generation also provides an increased secondary reactor temperature, thereby improving the overall thermal efficiency of the process. The means of in-situ oxygen is not restricted to one particular embodiment, and can occur using an oxygen generation reactor, an ion transport membrane, or both. A system configured to the second stage combustion method is also disclosed.

19 Claims, 4 Drawing Sheets

Staged chemical looping combustion process with integrated oxygen generation.



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CPC ***F23C 99/00*** (2013.01); ***F23L 7/007*** (2013.01); *F23C 2900/99008* (2013.01); *Y02E 20/344* (2013.01); *Y02E 20/346* (2013.01)

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FIG 1:
Staged chemical looping combustion process with integrated oxygen generation.

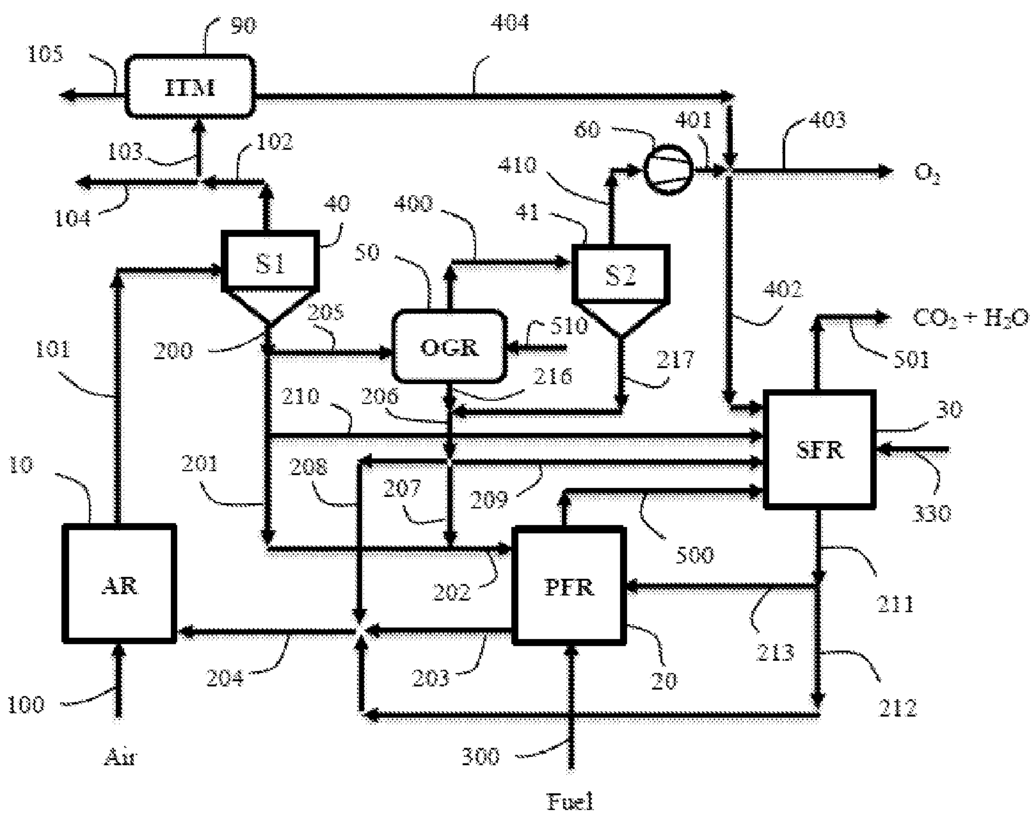


FIG 2:
Staged chemical looping combustion process with integrated oxygen generation using an ion transport membrane.

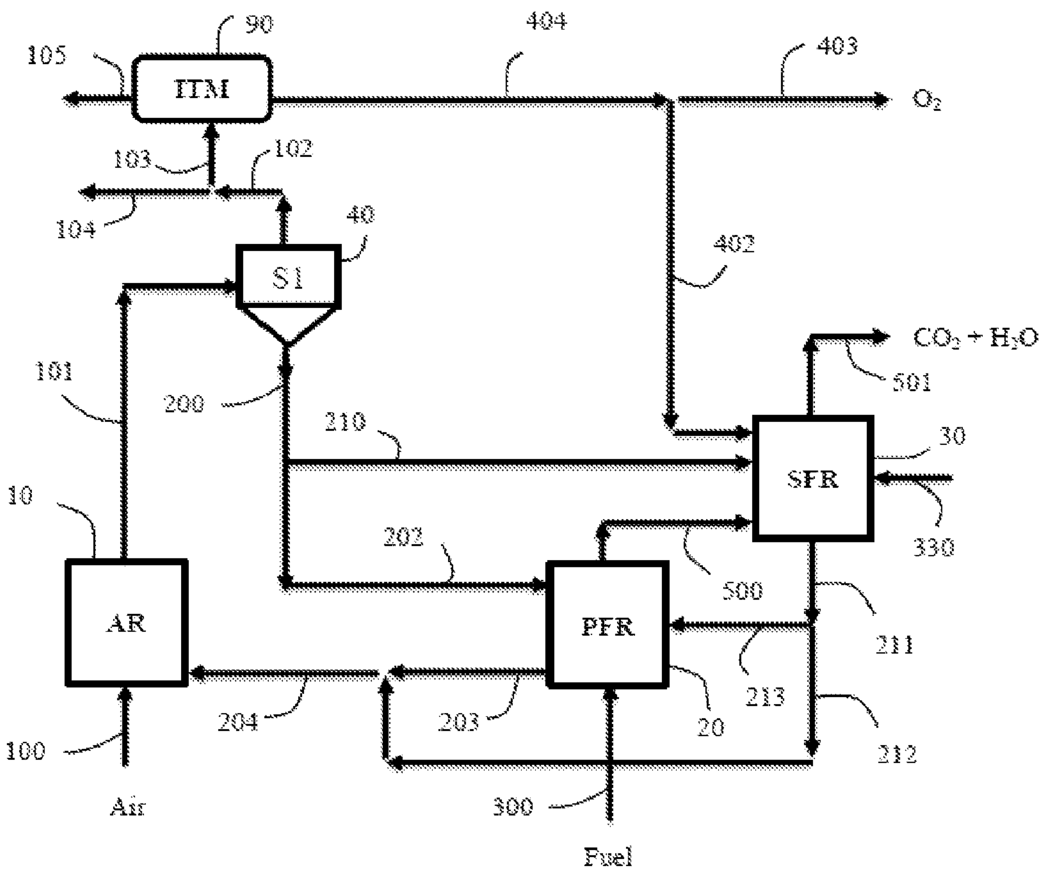


FIG. 3:
Staged chemical looping combustion process with integrated oxygen generation using an oxygen generation reactor.

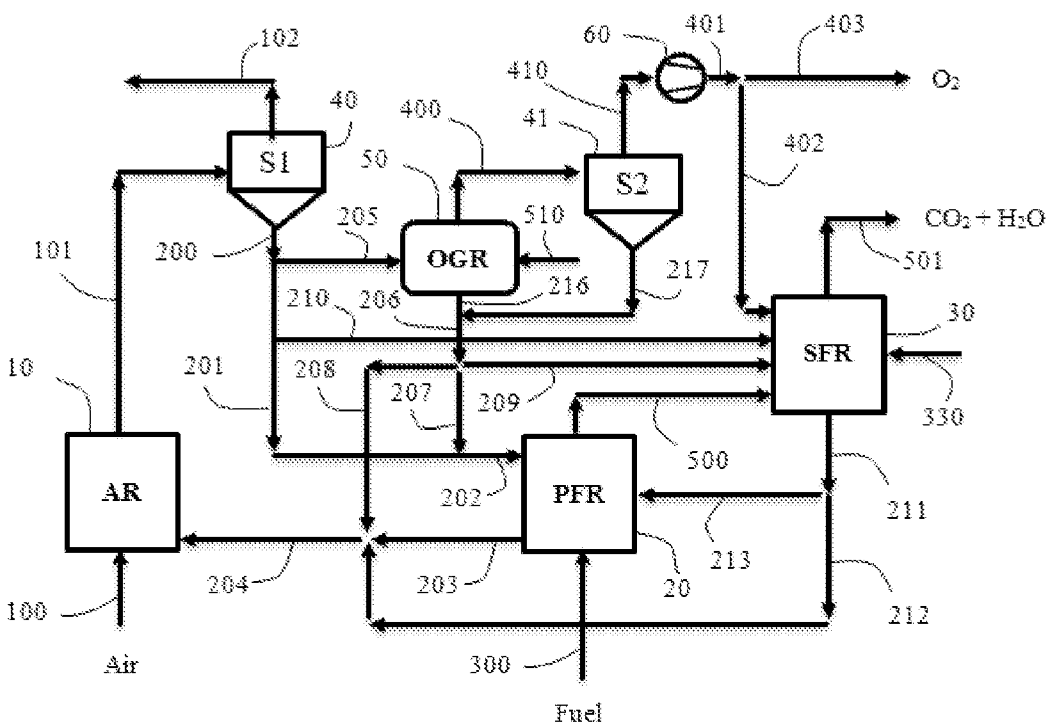
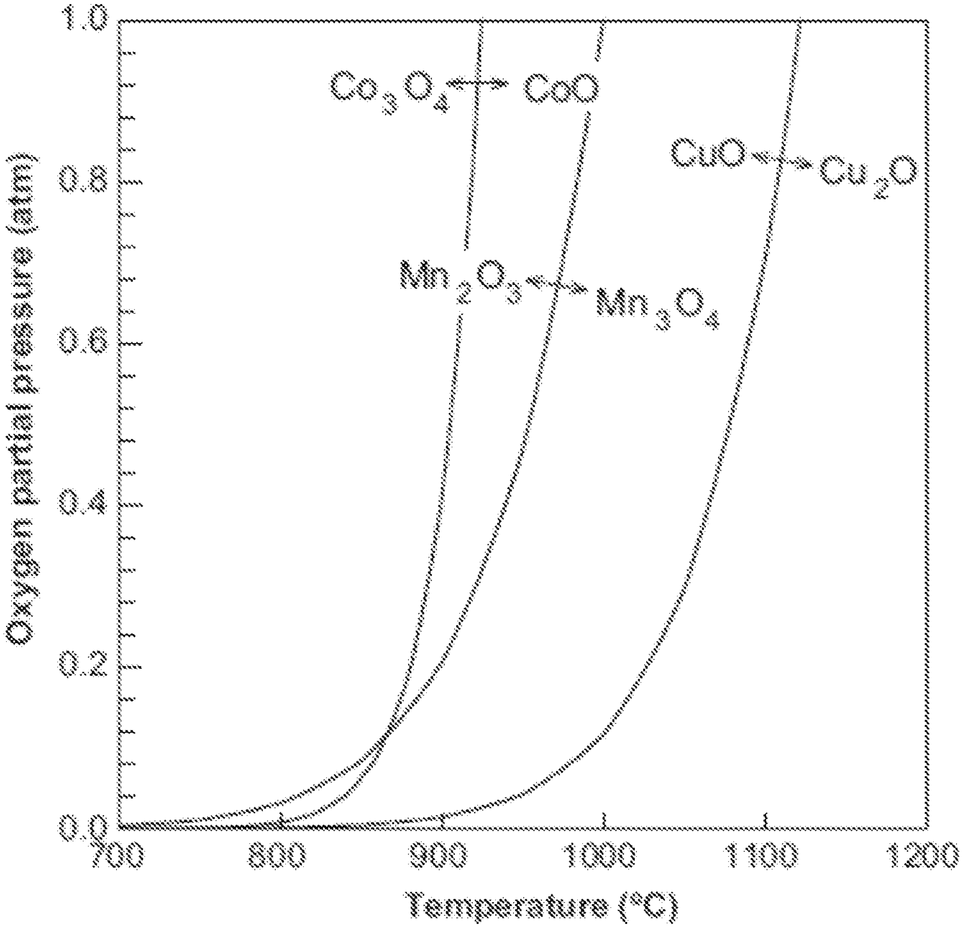


FIG. 4

Equilibrium partial pressure of gaseous O_2 over different metal oxide systems



STAGED CHEMICAL LOOPING PROCESS WITH INTEGRATED OXYGEN GENERATION

RELATED APPLICATION

This application is related to, and claims priority to, U.S. Provisional Patent Application Ser. No. 61/732,069, filed on Nov. 30, 2012, the disclosure of which is incorporated herein by reference in its entirety.

BACKGROUND

Field of the Invention

Embodiments of the invention generally relate to a fuel combustion process and system. More specifically, embodiments of the invention relate to a two-stage combustion method and system which uses in-situ oxygen generation to combust a fuel and produce a carbon dioxide (CO_2) rich flue gas stream from which CO_2 can be captured for later utilization and/or sequestration.

Description of the Related Art

Greenhouse gas concentration in the atmosphere has increased significantly over the past years as a result of increasing CO_2 emissions. Several mitigation techniques, including, for example, CO_2 capture and sequestration (CCS), are being investigated to reduce CO_2 emissions in the atmosphere.

One way of reducing CO_2 emissions is to capture the CO_2 from exhaust flue gases. Several conventional techniques are being developed to capture CO_2 before or after combustion. When the combustion of the fuel occurs with atmospheric air, the presence of nitrogen in the air dilutes the CO_2 concentration in the flue gases, penalizing the separation of the CO_2 from the flue gases.

Several additional conventional techniques are being evaluated to capture CO_2 from industrial exhaust flue gases to overcome the limitations of conventional gas separation processes. These conventional techniques, however, are often cost prohibitive to operate. Flue gases produced from conventional combustion are therefore typically treated to capture the CO_2. The low concentration level of CO_2 in the flue gases results from the use of air (i.e., containing nitrogen) as the source of oxygen to drive the combustion reaction.

Another such conventional technique is chemical looping combustion (CLC), in which oxygen is transferred to fuel without nitrogen interference, thereby generating a CO_2 and water vapor stream after the fuel is oxidized. The water vapor can then be easily removed (i.e., through condensation), leaving a higher purity CO_2 stream ready for compression, transportation, and/or processing. For at least these reasons, CLC is extensively investigated as a viable means for reducing CO_2 emissions. Chemical looping is based on an oxygen carrier that can be oxidized in the presence of air and reduced in the presence of fuel, thereby transferring the oxygen from the air to the fuel. The oxygen carrier is oxidized in an air reactor where it reacts with oxygen present in the air to form metal oxide or oxygen carrier oxide. The oxidized oxygen carrier is fed subsequently to a fuel reactor in a reducing atmosphere where the oxidized oxygen carrier transfers its oxygen to the fuel, thereby allowing the reduced oxygen carrier to be used for another phase of oxidation with air. The fuel is oxidized in the fuel reactor to form combustion products among CO, CO_2, and H_2O, based on the level of fuel oxidation and whether the chemical looping process is for combustion or reforming.

Several oxygen carriers have been investigated for CLC. It has been found that some oxygen carriers have the characteristic of releasing gaseous oxygen in a fuel reactor, thereby enhancing the oxidation or combustion of fuels. Several oxygen carriers are being investigated for chemical looping processes and no oxygen carrier has been found to address all the challenges faced by conventional oxygen carriers (e.g., oxygen transport capacity, high reactivity, resistance to attrition, cost, lifetime, etc.). It is difficult to achieve full conversion of the fuel in many cases and oxygen polishing have been considered for completeness of the combustion. In such cases, the required oxygen is provided by an external source."

In-situ oxygen generation, for example, allows the operation of a second oxidation step in which all the fuel can be completely oxidized, maximizing fuel conversion efficiency. Furthermore, by increasing the flue gas temperature generated after oxygen combustion or oxidation, higher live steam temperatures, in the case of power generation, can be generated, thereby increasing the overall thermal efficiency of the process.

SUMMARY

Generally, embodiments of the invention are directed to methods of two-stage fuel combustion with integrated oxygen generation. Various embodiments provide chemical looping combustion processes where oxygen is transferred from air to fuel to partially or completely oxidize the fuel. As will be discussed in more detail below, in-situ oxygen generation, according to various embodiments, provides a second oxidation stage to further combust the fuel, resulting in a CO_2 rich flue gas stream from which CO_2 can be captured for later utilization and/or sequestration. The staged chemical looping combustion process, according to various embodiments of the invention, reduces the need to post-treat the CO_2 after the combustion process, resulting in cost savings.

Various embodiments demonstrate that independent of the bed configurations of an air reactor or a fuel reactor used in a conventional combustion process, it is possible to incorporate an oxygen carrier having the property of releasing gaseous oxygen under specific conditions called a Chemical Looping Oxygen Coupling (CLOU) effect, thereby enhancing fuel oxidation. In particular, the staged chemical looping combustion process, according to embodiments of the invention, uses an oxygen carrier with the CLOU effect to oxidize the fuel in a fuel reactor in a first stage, followed by the completion of the oxidation of the fuel in a second stage using pure oxygen generated by the oxygen released from the oxygen carrier with the CLOU effect.

According to at least one embodiment, a separator, for example, a solid/gas separator, is positioned downstream of an air reactor, for example, a circulating fluidized bed air reactor, to separate the oxidized oxygen carrier from oxygen-lean air. Hot oxygen-lean air is processed to generate energy, heat, and/or power, while the oxidized oxygen carrier is split into two streams: (1) a first stream feeding the fuel reactor, and (2) a second stream feeding the oxygen generator. The oxygen generator, according to one embodiment, is a heated bed with controlled pressure that releases gaseous oxygen from the oxygen carrier under appropriate temperature and pressure conditions.

In accordance with another embodiment, the hot oxygen-lean air is fed to an ion transport membrane (ITM) to generate gaseous oxygen that is combined with the gaseous oxygen produced from the heated bed. In this embodiment, any oxygen carrier can be used, since the required in-situ gaseous oxygen is produced from the ITM.

The generated gaseous oxygen is then conveyed to the second oxidation stage, where the fuel is completely oxidized. The reduced oxygen carrier is conveyed back to the air reactor or to the fuel reactor based on the level of reduction, thereby completing the cycle.

Therefore, in accordance with one embodiment, there is provided a method of two-stage combustion integrating in situ oxygen generation. The method includes oxidizing, using an air reactor, a reduced oxygen carrier stream to form an oxidized oxygen carrier stream, and separating, in a primary separator, an oxygen carrier and oxygen-depleted air from the oxidized oxygen carrier stream. The method further includes producing, in an oxygen generation system, gaseous oxygen. Further, the method includes combusting, using a primary fuel reactor, fuel in the presence of the oxygen carrier and combusting, using a secondary fuel reactor, at least one of an additional fuel supply and an unburned fuel exiting the primary fuel reactor in the presence of the gaseous oxygen.

In accordance with another embodiment of the invention, there is provided a method of two-stage combustion integrating in situ oxygen generation, which includes generating the gaseous oxygen in an ITM of the oxygen generation system.

In accordance with another embodiment of the invention, there is provided a method of two-stage combustion integrating in situ oxygen generation, which includes generating the gaseous oxygen in an oxygen generation reactor (OGR) of the oxygen generation system.

In accordance with at least one embodiment, the step of oxidizing includes oxidizing the reduced oxygen carrier stream using one of a riser reactor and a fluidized bed reactor

In accordance with at least one embodiment, the step of combusting includes combusting the fuel using the primary fuel reactor being one of a fluidized bed reactor and a moving bed reactor.

In accordance with at least one embodiment, the step of combusting the at least one of the additional fuel supply and the unburned fuel exiting the primary fuel reactor includes combusting such a fuel using an oxy-fuel boiler or any type of a combustion chamber.

In accordance with at least one embodiment, the step of producing includes generating the gaseous oxygen in an ion transport membrane of the oxygen generation system for one of internal use or as a utility.

In accordance with at least one embodiment, the step of generating the gaseous oxygen in the ion transport membrane includes separating oxygen from the oxygen-depleted air leaving the primary separator.

In accordance with at least one embodiment, the step of producing includes generating the gaseous oxygen in an oxygen generation reactor of the oxygen generation system for one of internal use or as a utility.

In accordance with at least one embodiment, the oxygen carrier leaving the primary separator enters at least one of the primary fuel reactor, the oxygen generation reactor, and the secondary fuel reactor.

In accordance with at least one embodiment, the step of producing includes generating the gaseous oxygen in the oxygen generation reactor by at least one of increasing pressure of the oxygen generation reactor, adjusting the oxygen generation reactor temperature, and injecting a sweep gas, in the presence of the oxygen carrier. The sweep gas is selected from the group consisting of carbon dioxide and steam.

In accordance with at least one embodiment, the method further includes the step of separating, in a secondary separator, the gaseous oxygen and the oxygen carrier.

In accordance with another embodiment, there is provided a system for two-stage combustion integrating in situ oxygen generation, which includes an air reactor to oxidize a reduced oxygen carrier stream to form an oxidized oxygen carrier stream, a primary separator to separate an oxygen carrier and oxygen-depleted air from the oxidized oxygen carrier stream, an oxygen generation system to produce gaseous oxygen, a primary fuel reactor to combust fuel in the presence of the oxygen carrier, and a secondary fuel reactor to combust at least one of an additional fuel supply and an unburned fuel exiting the primary fuel reactor in the presence of the gaseous oxygen.

In accordance with at least one embodiment, the air reactor includes one of a riser reactor and a fluidized bed reactor.

In accordance with at least one embodiment, the primary fuel reactor includes one of a fluidized bed reactor and a moving bed reactor.

In accordance with at least one embodiment, the secondary fuel reactor further includes an oxy-fuel boiler or any type of a combustion chamber.

In accordance with at least one embodiment, the oxygen generation system includes an ion transport membrane.

In accordance with at least one embodiment, the ion transport membrane produces the gaseous oxygen by separating oxygen from the oxygen-depleted air leaving the primary separator.

In accordance with at least one embodiment, the oxygen generation system includes an oxygen generation reactor.

In accordance with at least one embodiment, the oxygen carrier leaving the primary separator enters at least one of the primary fuel reactor, the oxygen generation reactor, and the secondary fuel reactor.

In accordance with at least one embodiment, the oxygen generation reactor produces the gaseous oxygen by at least one of increasing pressure of the oxygen generation reactor, adjusting the oxygen generation reactor temperature, and injecting one of a sweep gas, in the presence of the oxygen carrier. The sweep gas is selected from the group consisting of carbon dioxide and steam.

In accordance with at least one embodiment, the system further includes a secondary separator configured to separate the gaseous oxygen and the oxygen carrier.

BRIEF DESCRIPTION OF THE DRAWINGS

So that the manner in which the features and advantages of the invention, as well as others which will become apparent, may be understood in more detail, a more particular description of the invention briefly summarized above may be had by reference to the embodiments thereof which are illustrated in the appended drawings, which form a part of this specification. It is to be noted, however, that the drawings illustrate only various embodiments of the invention and are therefore not to be considered limiting of the invention's scope as it may include other effective embodiments as well.

FIG. **1** is a flow diagram of a method showing a two-stage chemical looping combustion process integrating in-situ oxygen generation, in accordance with an embodiment of the invention.

FIG. **2** is a flow diagram of a method showing a two-stage chemical looping combustion process with integrating in-situ oxygen generation using an ITM, in accordance with an embodiment of the invention.

FIG. **3** is a flow diagram of a method showing a two-stage chemical looping combustion process with integrated oxygen generation using an OGR, in accordance with an embodiment of the invention.

FIG. **4** is a graph showing the equilibrium partial pressures of gas-phase O_2 over different metal oxide systems, in accordance with an embodiment of the invention.

DETAILED DESCRIPTION

The present invention will now be described more fully hereinafter with reference to the accompanying drawings, which illustrate embodiments of the invention. This invention may, however, be embodied in many different forms and should not be construed as limited to the illustrated embodiments set forth herein. Rather, these embodiments are provided so that this disclosure will be thorough and complete, and will fully convey the scope of the invention to those skilled in the art. Like numbers refer to like elements throughout.

Generally, embodiments of the invention are directed to methods for enhanced fuel combustion to maximize the capture of by-product CO_2 using a two-stage process for combustion with in-situ oxygen generation. The process, according to various embodiments of the invention, uses a chemical looping combustion process, for industrial applications including power, syngas, steam and heat (in general), or hydrogen production.

Embodiments of the invention provide for the combustion of fossil fuels, particularly liquid fuels, in a carbon constrained future, because a product stream of CO_2 and water vapor, from which water vapor, can be easily condensed and stripped off of the stream, producing a pure CO_2 stream to manage.

Embodiments of the invention further provide for a system that burns several fuel qualities and ensure that a complete conversion or oxidation of the fuel, thereby increasing process efficiency. The process, according to various embodiments, can be used to burn all types of fuels from solids to gases passing by liquid fuels, particularly heavy liquid fuels.

As shown in FIGS. **1**-**3**, various embodiments of the invention demonstrate that oxygen can be generated using an OGR, an ITM, or both. The chemical looping combustion process is based on integrated oxygen generation to complete fuel conversion, thereby increasing the efficiency of the process by increasing the fuel conversion efficiency and the temperature of the live steam.

As previously discussed, conventional chemical looping combustion processes use a single fuel reactor to oxidize or combust the fuel. Embodiments of the invention, on the other hand, provide fuel conversion using at least two stages, with a first stage including a fuel reactor (e.g., a fluidized bed or a moving bed fuel reactor), subsequently followed by a second stage including a combustion chamber or an oxy-fuel boiler using oxygen produced from the chemical looping combustion process that allows full conversion of the processed fuel, thereby producing a higher products stream temperature outlet that contributes to an increased process efficiency.

The two-stage chemical looping combustion process, according to various embodiments, includes fuel combustion reactors, oxygen generation by ITM and/or oxygen generation using an oxygen carrier having a CLOU effect, and an oxy-fuel combustion/oxidation process. Besides the staged oxidation/combustion reaction to achieve high fuel conversion, gaseous oxygen generation is provided by an in-situ oxygen generation process based on an ITM and/or a CLOU effect, providing an integrated and more efficient design.

Two-Stage Chemical Looping Combustion Process Integrating In-Situ Oxygen Generation

FIG. **1** is a flow diagram of a method showing a two-stage chemical looping combustion process integrating in-situ oxygen generation, in accordance with an embodiment of the invention. As shown in FIG. **1**, the two-stage chemical looping combustion process, according to at least one embodiment of the invention, utilizes air stream **100**, which enters an air reactor (AR) **10** to oxidize incoming reduced oxygen carrier stream **204**, which contains a reduced oxygen carrier. The resulting oxidized oxygen-carrier stream **101** is processed in a primary separator (S**1**) (e.g., a gas/solid separator) **40**, where the oxygen-depleted air exits the primary separator **40** via stream **102** and an oxidized oxygen carrier exits the primary separator **40** via another stream **200** (e.g., oxidized oxygen-carrier stream **200**). The oxygen-depleted air in stream **102** is conveyed for downstream processing, including, for example, power production and steam generation via another stream **104**. The remaining portion of stream **102** is conveyed to an ion transport membrane (ITM) **90** for oxygen generation via another stream **103**.

Ion Transport Membrane (ITM)

In accordance with various embodiments of the invention, the ITM **90**, as shown in FIG. **1**, separates the oxygen from the oxygen-depleted air. The produced gaseous oxygen is conveyed via stream **404** (e.g., oxygen stream **404**) for internal usage or conveyed out of the system as a utility. The oxygen-depleted air leaves the ITM **90** through stream **105** for further processing, including, for example, power production and steam generation. In at least one embodiment, streams **104** and **105** are combined. In accordance with at least one embodiment, the ITM **90** operates at the temperature of the air reactor **10**, which makes it easy to integrate the ITM **90** at the level of the oxygen-depleted air exiting the air reactor **10** (i.e., at stream **102** after the solid/gas separation in the primary separator **40**, as shown in FIG. **1**, or at stream **101** before the solid/gas separation in the primary separator **40**), or inside the air reactor **10**.

Oxygen Generation Reactor (OGR)

In accordance with various embodiments of the invention, oxidized oxygen-carrier stream **200** exiting the primary separator **40**, as shown in FIG. **1**, is split into stream **201** (e.g., oxidized oxygen-carrier stream **201**) heading to a primary fuel reactor (PFR) **20**, stream **205** (e.g., oxidized oxygen-carrier stream **205**) heading to an oxygen generation reactor (OGR) **50**, and stream **210** (e.g., oxidized oxygen-carrier stream **210**) heading to a secondary fuel reactor (SFR) **30**. In accordance with various embodiments, the flow ratios of streams **201**, **205**, and **210** can vary depending on the desired application of the chemical looping combustion process. Accordingly, in at least one embodiment, the flow of oxidized oxygen-carrier stream **210** is zero, depending on the system configuration, purpose, and the secondary fuel reactor **30** type.

The oxidized oxygen carrier in oxidized oxygen-carrier stream **201** enters the primary fuel reactor **20** via stream **202**, where the oxidized oxygen carrier reacts with fuel introduced into the primary fuel reactor **20** via fuel feed stream **300**. The fuel is oxidized in the primary fuel reactor **20**, thereby reducing the oxidized oxygen carrier. The resulting oxygen-depleted stream containing the reduced oxygen carrier exits the primary fuel reactor **20** via stream **203** and is conveyed to the air reactor **10** via reduced oxygen carrier stream **204** for another cycle.

As further shown in FIG. **1**, oxidized oxygen-carrier stream **205** enters the OGR **50** that is operated, for example, at a pressure and a temperature that enables the oxygen carrier to release gaseous oxygen in the OGR **50**. In accordance with at least one embodiment, oxygen is recovered from the oxygen carrier by, for example, increasing a reactor pressure at a specific temperature or by injecting a sweep gas, such as CO_2 or steam.

For example, in accordance with one embodiment, depending on the system pressure, the gaseous oxygen is recovered via a vacuum pump or an extractor fan **60**, as an example, that acts as a pressure increasing device to convey the oxygen out of the OGR **50**. The rate of oxygen generation in the OGR **50** is adjusted by controlling the temperature and/or the pressure of the OGR **50** via the vacuum pump or the extractor fan **60**. This embodiment is preferred if oxygen has to be produced as a utility and pure oxygen is required.

For example, in accordance with another embodiment, CO_2 and/or steam is injected into the OGR **50** via stream **510** to carry the gaseous oxygen from the OGR **50**, via stream **400** (e.g., gaseous oxygen stream **400**). The rate of oxygen generation in the OGR **50** is adjusted by controlling the flow rate of stream **510**. This embodiment is preferred if the oxygen does not require a specific purity and the presence of a sweep gas is acceptable, and therefore a vector gas or sweep gas injection into the OGR **50** can be used to recover the oxygen.

If a sweep gas option is considered for the oxygen recovery from the OGR **50**, it is possible to route a slip stream of products stream **501** (as will be discussed in more detail below) to the OGR **50** via stream **510** to generate the required oxygen that could be used in the secondary fuel reactor **30**. Doing so can increase the recirculation rate, since part of products stream **501** is introduced indirectly into the secondary fuel reactor **30** via streams **510**, **400**, **410**, **401**, and **402**. Combining the sweep gas oxygen recovery to the vacuum pump or extractor fan recovery technique allows for the control of the oxidation temperature in the secondary fuel reactor **30** by controlling the recirculation rate in the secondary fuel reactor **30**, which gives increased flexibility to the system.

Gaseous oxygen stream **400** is processed in a secondary separator (S**2**) **41**, where the separated oxygen exits the secondary separator **41** via stream **410** (e.g., gaseous oxygen stream **410**), and the oxygen carrier exits the secondary separator **41** via stream **217**. The gaseous oxygen stream **410** is conveyed to the secondary fuel reactor **30** via streams **401** (e.g., a oxygen stream **401**) and **402**. In accordance with an embodiment, the oxygen stream **401** meets oxygen stream **404** from the ITM **90** before it splits into stream **402** entering the secondary fuel reactor **30** and stream **403** exiting the chemical looping combustion process as a utility.

In accordance with at least one embodiment, stream **401** and oxygen stream **404** are diverted entirely to stream **402**. In accordance with another embodiment, stream **401** and oxygen stream **404** are diverted entirely to stream **403** for delivering the oxygen as a utility. In this embodiment, the process can be run without second stage combustion or without supplied gaseous oxygen stage combustion. In accordance with yet another embodiment, stream **401** and oxygen stream **404** are distributed between streams **402** and **403** depending on the oxygen requirements for each flow. In accordance with a yet another embodiment, stream **403** and oxygen stream **404** are injected into the primary fuel reactor **20** to increase the oxidation rate in the OGR **50**. In accordance with yet another embodiment, the oxygen in oxygen stream **404** is used as a utility, while the oxygen in stream **401** is used internally. This final embodiment is dependent on the purity and oxygen recovery method used for recovery of the oxygen from the oxygen carrier particles in the OGR **50**, as will be discussed in more detail below.

The process according to various embodiments, as shown in FIG. **1**, generates oxygen for use internally, externally, or both. This is possible, for example, by adjusting the flow ratio of oxidized oxygen-carrier stream **200** between the primary fuel reactor **20** and the OGR **50**, and further by adjusting the flow of the produced gaseous oxygen in the ITM **90** by varying the flow ratio between streams **103** and **104**.

Fuel Reactors

As noted above, the oxygen generation from the OGR **50** can be controlled by controlling the temperature and/or the pressure of the OGR **50** via vacuum pump or an extractor fan **60**, in the case of an increased pressure oxygen generation scheme, or by controlling the flow rate of stream **510**, in the case of a sweep gas oxygen recovery scheme.

In accordance with various embodiments, the reduced oxygen carrier in the OGR **50** exits the OGR **50** via stream **216**. Stream **217** joins stream **216** to form stream **206**. As shown in FIG. **1**, stream **206** can be conveyed to the primary fuel reactor **20** via stream **207** and/or to the air reactor **10** via stream **208** and/or to the secondary fuel reactor **30** via stream **209**. In a preferred embodiment, stream **206** is conveyed directly to the air reactor **10**. In accordance with various embodiments, the flow rates of streams **207**, **208**, and **209** vary, for example, from 0% to 100% of the initial flow rate of stream **206** depending on the system configuration, application, and level of reduction of the oxygen carrier in stream **206**.

For example, in accordance with one embodiment, the oxygen carrier of stream **206** is fully reduced. In this embodiment, the oxygen carrier in stream **206** is preferably conveyed via stream **208** to the air reactor **10**, while joining stream **203** from the primary fuel reactor **20** to enter the air reactor **10** via reduced oxygen carrier stream **204**. In another embodiment, the oxygen carrier of stream **206** is lightly reduced. In this embodiment, the oxygen carrier withstands more reduction in the primary fuel reactor **20** and/or the secondary fuel reactor **30**. The oxygen carrier in stream **206** is then conveyed via stream **207** to meet oxidized oxygen-carrier stream **201** and enter the primary fuel reactor **20** via stream **202** and/or be conveyed via stream **209** to enter the secondary fuel reactor **30**.

As further shown in FIG. **1**, gaseous stream **500**, in accordance with an embodiment, exits the primary fuel reactor **20** and is introduced to the secondary fuel reactor **30** to oxidize the remaining fuel and increase the efficiency of the process. Products stream **501** generally discussed above is sent for downstream processing, including, for example, energy recovery, steam generation, and utilities supply.

In accordance with at least one embodiment, the secondary fuel reactor **30** is, for example, an oxidizing reactor operated by, for example, gaseous oxygen with or without oxygen carriers and with or without fuel introduction depending on the scheme and purpose of the process. In a preferred embodiment of the process for power generation, the secondary fuel reactor **30** is a boiler operated by oxy-fuel combustion with the oxygen being delivered via stream **402** produced in-situ.

In accordance with certain embodiments, it is possible to use part or all of gaseous stream **500** exiting the primary fuel reactor **20** to control the temperature in the secondary fuel reactor **30**. In accordance with certain embodiments of the invention, it is possible to recycle stream **501** exiting the secondary fuel reactor, **30**, to control the temperature in the secondary fuel reactor, **30**. The use of an oxy-boiler in the secondary fuel reactor **30** provides a higher flue gas temperature in the stream **501**, leading to a higher live stream temperature in a power generation scheme, thereby increasing the efficiency of the chemical looping combustion process.

In some embodiments, the chemical looping combustion process is designed for combustion and CO_2 capture. In such embodiments, products stream **501** is composed mainly of CO_2 and steam. In such a case, it is possible to condense the steam and drain it from the products stream **501**, leaving high purity CO_2 in products stream **501**. The CO_2 can then be further processed depending on the CO_2 quality required.

In some embodiments, the secondary fuel reactor **30** is fed by oxygen carriers via stream **209** and/or stream **210**. In such embodiments, the oxygen carrier is reduced in the secondary fuel reactor **30** and exits through stream **211**. The oxygen carrier in the stream **211** is fed to the primary fuel reactor **20** via stream **213** and/or conveyed for oxidation in the air reactor **10** via streams **212** and reduced oxygen carrier stream **204**. The secondary fuel reactor **30** includes a fuel stream **330**.

The process according to various embodiments of the invention, as shown in FIG. **1**, are operated at ambient pressure or near ambient pressure. The process can also be operated at high pressure. In certain embodiments, the air reactor **10** is operated at atmospheric pressure. In such embodiments, the air reactor **10** includes an extractor fan (not shown) at the stream **102** and/or at oxygen stream **404** to create a pressure difference and transport the produced gaseous oxygen via the oxygen stream **404**.

Two-Stage Chemical Looping Combustion Process Integrating In-Situ Oxygen Generation Using ITM

FIG. **2** is a flow diagram of a method showing a two-stage chemical looping combustion process integrating in-situ oxygen generation using an ITM, in accordance with an embodiment of the invention. FIG. **2** contains similar elements as discussed above for the two-stage chemical looping combustion process shown in FIG. **1**, as represented with like numbers, and as discussed above. The two-stage chemical looping combustion process, as shown in FIG. **2**, is distinguished from the two-stage chemical looping combustion process, as shown in FIG. **1**, in that it eliminates the OGR **50** and all associated streams and processes to and from the OGR **50** discussed above for the two-stage chemical looping combustion process shown in FIG. **1**. Furthermore, the two-stage chemical looping combustion process shown in FIG. **2** does not include the secondary separator **41** or the vacuum pump/extractor fan **60** discussed above for the two-stage chemical looping combustion process shown in FIG. **1**.

Similarly for the two-stage chemical looping combustion process shown in FIG. **1**, the ITM **90** separates the oxygen from the oxygen-depleted air. The produced gaseous oxygen is conveyed via oxygen stream **404** for internal usage (i.e., to feed the secondary fuel reactor **30** via stream **402**) and/or conveyed out of the system as a utility via stream **403**. The oxygen-depleted air leaves the ITM **90** through the stream **105** for further processing, including, for example, power production and steam generation. In at least one embodiment, streams **104** and **105** are combined.

As discussed above for the two-stage chemical looping combustion process shown in FIG. **1**, the two-stage chemical looping combustion process shown in FIG. **2** uses an ITM that operates at the temperature of the air reactor **10**, which makes it easy to integrate the ITM **90** at the level of the oxygen-depleted air exiting the air reactor **10** (i.e., at stream **102** after the solid/gas separation in the primary separator **40**, as shown in FIG. **2**, or at stream **101** before the solid/gas separation in the primary separator **40**), or inside the air reactor **10**.

As further shown in FIG. **2**, oxidized oxygen carrier stream **200** exiting the primary separator **40** is split into stream **202** heading to the primary fuel reactor **20**, and oxidized oxygen-carrier stream **210** heading to a secondary fuel reactor **30**. Depending on the system configuration, purpose, and type of the secondary fuel reactor **30**, the flow rate of oxidized oxygen-carrier stream **210** may be zero. In accordance with an embodiment, the ratio of the flow rates between streams **202** and the oxidized oxygen-carrier stream **210** vary depending on the application of the chemical looping combustion process and system transitions (e.g., cold start transitions).

The oxidized oxygen carrier in stream **200** enters the primary fuel reactor **20** via stream **202**, where the oxidized oxygen carrier reacts with fuel introduced into the primary fuel reactor **20** via a fuel feed stream **300**. The fuel is oxidized in the primary fuel reactor **20**, thereby reducing the oxidized oxygen carrier. The resulting oxygen-depleted stream containing the reduced oxygen carrier exits the primary fuel reactor **20** via stream **203** and is conveyed to the air reactor **10** via reduced oxygen carrier stream **204**.

In accordance with one embodiment, the entire oxygen stream **404** is diverted entirely to stream **402** to carry out the two-stage chemical looping combustion process. In accordance with another embodiment, oxygen stream **404** is diverted entirely to stream **403** for delivering oxygen as a utility. In this embodiment, the process can be run without second stage combustion or without supplied gaseous oxygen stage combustion. In accordance with yet another embodiment, oxygen stream **404** is distributed between streams **402** and **403** depending on the oxygen requirements for each flow. In accordance with a yet another embodiment, oxygen stream **404**, in part or in whole, is injected into the primary fuel reactor **20** (not shown) to increase the oxidation rate in the primary fuel reactor **20**.

The process according to various embodiments, as shown in FIG. **2**, generates oxygen for use internally, externally, or both. This is possible, for example, by adjusting the flow of oxygen generated in the ITM **90** by varying the flow ratio between streams **103** and **104**.

As similarly shown in FIG. **1**, gaseous stream **500**, as shown in FIG. **2**, exits the primary fuel reactor **20** and is introduced to the secondary fuel reactor **30** to oxidize the remaining fuel and increase the efficiency of the process. Products stream **501** generally discussed above is sent for downstream processing, including, for example, energy recovery, steam generation, and utilities supply.

In accordance with at least one embodiment, the secondary fuel reactor **30** is, for example, an oxidizing reactor operated by, for example, gaseous oxygen with or without oxygen carriers and with or without fuel introduction depending on the scheme and purpose of the process. In a preferred embodiment of the process for power generation, the secondary fuel reactor **30** is a boiler operated by oxy-fuel combustion with the oxygen being delivered via stream **402** produced in-situ.

In accordance with an embodiment, it is possible to use part or all of gaseous stream **500** exiting the primary fuel reactor **20** to control the temperature in the secondary fuel reactor **30**. In accordance with certain embodiments of the invention, it is possible to recycle stream **501** exiting the secondary fuel reactor, **30**, to control the temperature in the secondary fuel reactor, **30**. The use of an oxy-boiler in the secondary fuel reactor **30** provides a higher flue gas temperature in stream **501**, leading to a higher live stream temperature in a power generation scheme, thereby increasing the efficiency of the chemical looping combustion system.

In some embodiments, the chemical looping combustion process, as shown in FIG. **2**, is designed for combustion and CO_2 capture. In such embodiments, products stream **501** is composed mainly of CO_2 and steam. In such a case, it is possible to condense the steam and drain it from products stream **501**, leaving high purity CO_2 in products stream **501**. The CO_2 can then be further processed depending on the CO_2 quality required.

In some embodiments, the secondary fuel reactor **30** is fed by oxygen carriers via stream **210**. In such embodiments, the oxygen carrier is reduced in the secondary fuel reactor **30** and exits through stream **211**. The oxygen carrier in stream **211** is fed to the primary fuel reactor **20** via stream **213** and/or conveyed for oxidation in the air reactor **10** via streams **212** and reduced oxygen carrier stream **204**. The secondary fuel reactor **30** includes fuel stream **330**.

The process according to various embodiments of the invention, as shown in FIG. **2**, is operated at ambient pressure or near ambient pressure. The process can also be operated at high pressure. In certain embodiments, the air reactor **10**, the primary fuel reactor **20**, and the secondary fuel reactor **30** are operated at the same pressure, while in other embodiments, they are operated at different pressures. In such embodiments, the air reactor **10** includes an extractor fan (not shown) at stream **102** and/or at oxygen stream **404** to create a pressure difference and transport the produced gaseous oxygen via oxygen stream **404**.

Two-Stage Chemical Looping Combustion Process Integrating In-Situ Oxygen Generation Using OGR

FIG. **3** is a flow diagram of a method showing a two-stage chemical looping combustion process integrating in-situ oxygen generation using an OGR, in accordance with an embodiment of the invention. FIG. **3** contains similar elements as discussed above for the two-stage chemical looping combustion process shown in FIG. **1**, as represented with like numbers, and as discussed above. The two-stage chemical looping combustion process, as shown in FIG. **3**, is distinguished from the two-stage chemical looping combustion process, as shown in FIG. **1**, in that it eliminates the ITM **90** and all associated streams and processes to and from the ITM **90** discussed above for the two-stage chemical looping combustion process shown in FIG. **1**.

Similar to the two-stage chemical looping combustion process shown in FIG. **1**, the two-stage chemical looping combustion process, as shown in FIG. **3**, utilizes air stream **100**, which enters the air reactor **10** to oxidize incoming reduced oxygen carrier stream **204**, which contains a reduced oxygen carrier. The resulting oxidized oxygen-carrier stream **101** is processed in a primary separator **40**, where the oxygen-depleted air exits the primary separator **40** via stream **102** and the oxidized oxygen carrier exits the primary separator **40** via oxidized oxygen-carrier stream **200**. The oxygen-depleted air in stream **102** is conveyed for downstream processing, including, for example, power production and steam generation.

In accordance with some embodiments, oxidized oxygen-carrier stream **200** exiting the primary separator **40**, as shown in FIG. **3**, is split into oxidized oxygen-carrier stream **201** heading to a primary fuel reactor **20**, oxidized oxygen-carrier stream **205** heading to the OGR **50**, and oxidized oxygen-carrier stream **210** heading to a secondary fuel reactor **30**. In accordance with various embodiments, the flow ratios of streams **201**, **205**, and **210** can vary depending on the desired application of the chemical looping combustion process. Accordingly, in at least one embodiment, the flow of oxidized oxygen-carrier stream **210** is zero, depending on the system configuration, purpose, and the secondary fuel reactor type.

The oxidized oxygen carrier in the oxidized oxygen-carrier stream **201** enters the primary fuel reactor **20** via a stream **202**, where the oxidized oxygen carrier reacts with fuel introduced into the primary fuel reactor **20** via a fuel feed stream **300**. The fuel is oxidized in the primary fuel reactor **20**, thereby reducing the oxidized oxygen carrier. The resulting reduced oxygen carrier stream containing the reduced oxygen carrier exits the primary fuel reactor **20** via stream **203** and is conveyed to the air reactor **10** via reduced oxygen carrier stream **204**.

As further shown in FIG. **3**, oxidized oxygen-carrier stream **205** enters the OGR **50** that is operated, for example, at a pressure and a temperature that enables the oxygen carrier to release gaseous oxygen in the OGR **50**. In accordance with at least one embodiment, oxygen is recovered from the oxygen carrier by, for example, increasing a reactor pressure at a specific temperature, adjusting the OGR **50** temperature for a given pressure, or by injecting a sweep gas, such as CO_2 or steam.

For example, in accordance with one embodiment, gaseous oxygen is recovered via a vacuum pump or an extractor fan **60** that acts as a pressure increasing device to convey the oxygen out of the OGR **50**. The rate of oxygen generation in the OGR **50** is adjusted by controlling the temperature and/or the pressure of the OGR **50** via the vacuum pump or the extractor fan **60**. This embodiment is preferred if oxygen has to be produced as a utility and pure oxygen is required.

For example, in accordance with another embodiment, CO_2 and/or steam is injected into the OGR **50** via stream **510** to carry the gaseous oxygen from the OGR **50**, via gaseous oxygen stream **400**. The rate of oxygen generation in the OGR **50** is adjusted by controlling the flow rate of stream **510**. This embodiment is preferred if the oxygen does not require a specific purity and the presence of a sweep gas is acceptable, and therefore a vector gas or sweep gas injection into the OGR **50** can be used to recover the oxygen.

If a sweep gas option is considered for the oxygen recovery from the OGR **50**, it is possible to route a slip stream of the products stream **501**, as discussed above for FIG. **1**, to the OGR **50** via stream **510** to generate the required oxygen that will be used in the secondary fuel reactor **30**. Doing so can increase the recirculation rate, since part of products stream **501** is introduced indirectly into the secondary fuel reactor **30** via streams **510**, **400**, **410**, **401**, and **402**. Combining the sweep gas oxygen recovery to the vacuum pump or extractor fan recovery technique allows for the control of the oxidation temperature in the secondary fuel reactor **30** by controlling the recirculation rate in the secondary fuel reactor **30**, which gives increased flexibility to the system.

Gaseous oxygen stream **400** is processed in the secondary separator **41**, where the separated oxygen exits the secondary separator **41** via gaseous oxygen stream **410**, and the oxygen carrier exits the secondary separator **41** via stream

217. Gaseous oxygen stream **410** is conveyed to the secondary fuel reactor **30** via oxygen stream **401** and stream **402**. In accordance with an embodiment, oxygen stream **401** splits into stream **402** entering the secondary fuel reactor **30** and stream **403** exiting the chemical looping combustion process as a utility.

In accordance with one embodiment, the oxygen stream **401** is diverted entirely to the stream **402** to carry out the two-stage chemical looping combustion process. In accordance with another embodiment, the oxygen stream **401** is diverted entirely to the stream **403** for delivering the oxygen as a utility. In this embodiment, the process can be run without second stage combustion or without supplied gaseous oxygen stage combustion. In accordance with a yet another embodiment, the stream **403**, in part or in whole, is injected into the primary fuel reactor **20** to increase the oxidation rate in the primary fuel reactor **20** (not shown).

The process according to various embodiments, as shown in FIG. **3**, generates oxygen for use internally, externally, or both. This is possible, for example, by adjusting the flow ratio of oxidized oxygen-carrier stream **200** between the primary fuel reactor **20** and the OGR **50**.

As noted above, the oxygen generation from the OGR **50** can be controlled by controlling the temperature and/or the pressure of the OGR **50** via vacuum pump or an extractor fan **60**, in the case of a reduced pressure oxygen generation scheme, adjusting the OGR **50** temperature for a given pressure, or by controlling the flow rate of stream **510**, in the case of a sweep gas oxygen recovery scheme.

In accordance with various embodiments, the reduced oxygen carrier in the OGR **50** exits the OGR **50** via stream **216**. Stream **217** joins stream **216** to form stream **206**. As shown in FIG. **3**, stream **206** can be conveyed to the primary fuel reactor **20** via stream **207** and/or to the air reactor **10** via stream **208** and/or to the secondary fuel reactor **30** via stream **209**. In a preferred embodiment, stream **206** is conveyed directly to the air reactor **10**. In accordance with various embodiments, the flow rates of the streams **207**, **208**, and **209** vary, for example, from 0% to 100% of the initial flow rate of stream **206** depending on the system configuration, application, and level of reduction of the oxygen carrier in stream **206**.

Similarly for the two-stage chemical looping combustion process shown in FIG. **1**, the oxygen carrier of the stream **206**, according to the two-stage chemical looping combustion process shown in FIG. **3**, can be fully reduced. In this embodiment, the oxygen carrier in stream **206** is preferably conveyed via stream **208** to the air reactor **10**, while joining stream **203** from the primary fuel reactor **20** to enter the air reactor **10** via reduced oxygen carrier stream **204**. In another embodiment, if the oxygen carrier of stream **206** is lightly reduced, the oxygen carrier withstands more reduction in the primary fuel reactor **20** and/or the secondary fuel reactor **30**. The oxygen carrier in stream **206** is then conveyed via stream **207** to meet the oxidized oxygen-carrier stream **201** and enters the primary fuel reactor **20** via stream **202** and/or be conveyed via stream **209** to enter the secondary fuel reactor **30**.

As further shown in FIG. **3**, gaseous stream **500**, in accordance with an embodiment, exits the primary fuel reactor **20** and is introduced to the secondary fuel reactor **30** to oxidize the remaining fuel and increase the efficiency of the process. Products stream **501** generally discussed above is sent for downstream processing, including, for example, energy recovery, steam generation, and utilities supply.

In accordance with at least one embodiment, the secondary fuel reactor **30** is, for example, an oxidizing reactor operated by, for example, gaseous oxygen with or without oxygen carriers and with or without fuel introduction depending on the scheme and purpose of the process. In a preferred embodiment of the process for power generation, the secondary fuel reactor **30** is a boiler operated by oxy-fuel combustion with the oxygen being delivered via stream **402** produced in-situ.

In accordance with certain embodiments, it is possible to use gaseous stream **500** exiting the primary fuel reactor **20** to control the temperature in the secondary fuel reactor **30**. In accordance with certain embodiments of the invention, it is possible to recycle stream **501** exiting the secondary fuel reactor, **30**, to control the temperature in the secondary fuel reactor, **30**. The use of an oxy-boiler in the secondary fuel reactor **30** provides a higher flue gas temperature in the stream **501**, leading to a higher live stream temperature in a power generation scheme, thereby increasing the efficiency of the chemical looping combustion process.

Similar to the embodiments discussed above for FIGS. **1** and **2**, the chemical looping combustion process, as shown in FIG. **3**, is designed for combustion and CO_2 capture. In such embodiments, products stream **501** is composed mainly of CO_2 and steam. In such a case, it is possible to condense the steam and drain it from products stream **501**, leaving high purity CO_2 in products stream **501**. The CO_2 can then be further processed depending on the CO_2 quality required.

Furthermore, in some embodiments, the secondary fuel reactor **30**, as shown in FIG. **3**, is fed by oxygen carriers via stream **209** and/or stream **210**. In such embodiments, the oxygen carrier is reduced in the secondary fuel reactor **30** and exits through stream **211**. The oxygen carrier in stream **211** is fed to the primary fuel reactor **20** via stream **213** and/or conveyed for oxidation in the air reactor **10** via streams **212** and reduced oxygen carrier stream **204**. The secondary fuel reactor **30** includes a fuel stream **330**.

Similar to the embodiments discussed above for FIG. **2**, the process according to various embodiments of the invention, as shown in FIG. **3**, is operated at ambient pressure or near ambient pressure. The process can also be operated at high pressure. In certain embodiments, the air reactor **10**, the primary fuel reactor **20**, and the secondary fuel reactor **30** are operated at the same pressure, while in other embodiments, they are operated at different pressures.

FIG. **4** is a graph showing the equilibrium partial pressures of gas-phase O_2 over different metal oxide systems. FIG. **4** further shows the CLOU effect of some oxygen carriers in contributing to complete fuel combustion or oxidation by gaseous O_2 to maximize system efficiency.

In accordance with various embodiments, the air reactor **10**, the primary fuel reactor **20**, and the secondary fuel reactor **30** is a type selected from a group consisting of a fluidized bed, a fast riser, a bubbling bed, a moving bed, a fixed bed, and a rotating bed. According to various embodiments, the secondary fuel reactor **30** further includes a combustion chamber or a boiler. One of ordinary skill in the relevant art would have understood that each reactor type has particular advantages and drawbacks, whereby the selection of the specific reactor type for each of the air reactor **10**, the primary fuel reactor **20**, and the secondary fuel reactor **30** is based on various factors discussed above for the various embodiments of the invention.

The present invention may suitably comprise, consist or consist essentially of the elements disclosed and may be practiced in the absence of an element not disclosed. For example, it can be recognized by those skilled in the art that certain steps can be combined into a single step.

Unless defined otherwise, all technical and scientific terms used have the same meaning as commonly understood by one of ordinary skill in the art to which this invention belongs.

The singular forms "a," "an," and "the" include plural referents, unless the context clearly dictates otherwise.

As used herein and in the appended claims, the words "comprise," "has," and "include" and all grammatical variations thereof are each intended to have an open, non-limiting meaning that does not exclude additional elements or steps.

"Optionally" means that the subsequently described event or circumstances may or may not occur. The description includes instances where the event or circumstance occurs and instances where it does not occur.

Ranges may be expressed herein as from about one particular value, and/or to about another particular value. When such a range is expressed, it is to be understood that another embodiment is from the one particular value and/or to the other particular value, along with all combinations within said range.

Although the present invention has been described in detail, it should be understood that various changes, substitutions, and alterations can be made hereupon without departing from the principle and scope of the invention. Accordingly, the scope of the present invention should be determined by the following claims and their appropriate legal equivalents.

What is claimed is:

1. A system for two-stage combustion integrating in situ oxygen generation, the system comprising:
- an air reactor configured to oxidize a reduced oxygen carrier stream to form an oxidized oxygen carrier stream comprising an oxygen carrier;
- a primary separator configured to separate the oxygen carrier and oxygen-depleted air from the oxidized oxygen carrier stream;
- an oxygen generation system comprising an oxygen generation reactor configured to produce gaseous oxygen;
- a primary fuel reactor configured to combust fuel in the presence of the oxygen carrier; and
- a secondary fuel reactor configured to combust at least one of an additional fuel supply and an unburned fuel exiting the primary fuel reactor in the presence of the gaseous oxygen produced in the oxygen generation system, wherein the secondary fuel reactor has conveyed to the secondary fuel reactor the oxygen carrier from the air reactor.

2. The system of claim **1**, wherein the air reactor comprises one of a riser reactor and a fluidized bed reactor.

3. The system of claim **1**, wherein the primary fuel reactor comprises one of a fluidized bed reactor and a moving bed reactor.

4. The system of claim **1**, wherein the secondary fuel reactor further comprises an oxy-fuel boiler or any type of a combustion chamber.

5. The system of claim **1**, wherein the oxygen generation system comprises an ion transport membrane.

6. The system of claim **5**, wherein the ion transport membrane is configured to produce the gaseous oxygen by separating oxygen from the oxygen-depleted air leaving the primary separator.

7. The system of claim **1**, wherein the oxygen carrier leaving the primary separator enters at least one of the primary fuel reactor, the oxygen generation reactor, and the secondary fuel reactor.

8. The system of claim **1**, wherein the oxygen generation reactor is configured to produce the gaseous oxygen by at least one of increasing pressure of the oxygen generation reactor, adjusting the oxygen generation reactor temperature, and injecting one of a sweep gas, the sweep gas selected from the group consisting of carbon dioxide and steam, in the presence of the oxygen carrier.

9. The system of claim **1**, further comprising:
- a secondary separator configured to separate the gaseous oxygen and the oxygen carrier.

10. A method of two-stage combustion integrating in situ oxygen generation, the method comprising:
- oxidizing, using an air reactor, a reduced oxygen carrier stream to form an oxidized oxygen carrier stream comprising an oxygen carrier;
- separating, in a primary separator, the oxygen carrier and oxygen-depleted air from the oxidized oxygen carrier stream;
- producing, in an oxygen generation system comprising an oxygen generation reactor, gaseous oxygen;
- combusting, using a primary fuel reactor, fuel in the presence of the oxygen carrier; and
- combusting, using a secondary fuel reactor, at least one of an additional fuel supply and an unburned fuel exiting the primary fuel reactor in the presence of the gaseous oxygen produced in the oxygen generation system, wherein the secondary fuel reactor has conveyed to the secondary fuel reactor the oxygen carrier from the air reactor.

11. The method of claim **10**, wherein the oxidizing comprises oxidizing the reduced oxygen carrier stream using one of a riser reactor and a fluidized bed reactor.

12. The method of claim **10**, wherein the combusting comprises combusting the fuel using the primary fuel reactor being one of a fluidized bed reactor and a moving bed reactor.

13. The method of claim **10**, wherein the combusting the at least one of the additional fuel supply and the unburned fuel exiting the primary fuel reactor comprises combusting such a fuel using an oxy-fuel boiler or any type of a combustion chamber.

14. The method of claim **10**, wherein the producing comprises generating the gaseous oxygen in an ion transport membrane of the oxygen generation system for one of internal use or as a utility.

15. The method of claim **14**, wherein the generating the gaseous oxygen in the ion transport membrane comprises separating oxygen from the oxygen-depleted air leaving the primary separator.

16. The method of claim **10**, wherein the producing comprises generating the gaseous oxygen in the oxygen generation system for one of internal use or as a utility.

17. The method of claim **16**, wherein the oxygen carrier leaving the primary separator enters at least one of the primary fuel reactor, the oxygen generation reactor, and the secondary fuel reactor.

18. The method of claim **16**, wherein the producing comprises generating the gaseous oxygen in the oxygen generation reactor by at least one of increasing pressure of the oxygen generation reactor, adjusting the oxygen generation reactor temperature, and injecting a sweep gas, the sweep gas selected from the group consisting of carbon dioxide and steam, in the presence of the oxygen carrier.

19. The method of claim **18**, further comprising:
- separating, in a secondary separator, the gaseous oxygen and the oxygen carrier.

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