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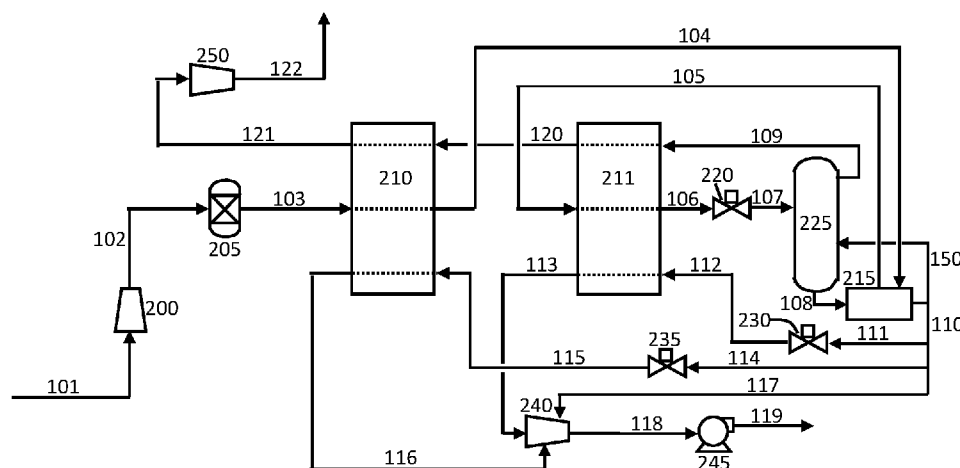


FIG. 1

(57) Abstract: The present disclosure relates to systems and methods useful for providing one or more chemical compounds in a substantially pure form. In particular, the systems and methods can be configured for separation of carbon dioxide from a process stream, such as a process stream in a hydrogen production system. As such, the present disclosure can provide systems and methods for production of hydrogen and/or carbon dioxide.

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SYSTEMS AND METHODS FOR PRODUCTION AND SEPARATION OF HYDROGEN AND CARBON DIOXIDE

FIELD OF THE INVENTION

5 The present disclosure provides systems and methods for producing materials that are typically gaseous at standard temperature and pressure, such as hydrogen and carbon dioxide. In particular, the present disclosure provides for separation of carbon dioxide from an industrial process stream, and specifically from a process stream that further includes hydrogen.

BACKGROUND

10 Hydrogen has long been viewed as a desirable energy source because of its clean combustion characteristics producing only water. Hydrogen can be produced from hydrocarbon fuels with capture of CO₂ avoiding any CO₂ emission to the atmosphere. Hydrogen can be a desirable commodity for use in fuel cells (particularly in vehicle production), heating applications,
15 oil refining, fertilizer production, and other chemical production. For example, hydrogen can be used as a fuel for electric vehicle propulsion using fuel cells advantageously coupled to high capacity electric storage batteries. Beneficially, use of hydrogen as a fuel can eliminate CO₂, NO_x, CO, and hydrocarbon emissions and thus significantly reduce air pollution particularly at ground level in large urban conurbations. Any path to implementation of a hydrogen-based world
20 economy, however, would require a very large hydrogen production capacity. Moreover, such hydrogen production method would need to be capable of achieving simultaneously low hydrogen production cost together with the capture of near 100% of the CO₂ and other impurities derived from any carbonaceous or hydrocarbon fuel utilized.

25 Hydrogen use as a fuel source can also be beneficial to reduce or eliminate carbon dioxide emissions associated with more conventional power production processes. For example, hydrogen can be diluted with nitrogen and/or steam and used as the fuel in a gas turbine combined cycle power generation system.

30 Gas turbine combined cycle power generation systems are a major source of electrical power generation worldwide because of their ability to produce power from natural gas with an efficiency in the range of 55% to 62%, on a lower heating value (LHV) basis. Despite the desirable efficiency, such systems are still problematic since the carbon in the fuel is emitted to the atmosphere as carbon dioxide. To overcome this problem and capture the CO₂ derived from fuel combustion a number of possibilities have been suggested. It is possible to operate the gas turbine with CO₂ in place of air as the working fluid by recycling the turbine exhaust back to the gas

turbine compressor inlet following cooling to generate steam for additional power production. The fuel for the gas turbine is burned with pure oxygen in an oxy-fuel burner so that all atmospheric nitrogen is eliminated from the closed cycle system and CO₂ becomes the working fluid in the gas turbine. The product CO₂ derived from fuel combustion together with condensed water are
5 removed upstream of the inlet of the gas turbine compressor section. Chemical and/or physical solvent scrubbing processes can be used to treat the gas turbine exhaust to remove CO₂. As discussed above, it is possible to eliminate the emissions of CO₂ and other fuel and combustion derived pollutants from the gas turbine exhaust by utilizing hydrogen as the fuel in the gas turbine. This approach requires a consistent high volume low cost hydrogen source that is preferentially
10 provided from a system in which substantially all the CO₂ and other fuel or combustion derived impurities are removed for separate disposal. Hydrogen production in excess of that required for gas turbine fuel can be provided from such a system for use in the wider applications for hydrogen as a fuel described above.

Other industrial processes are also known that utilize significant amounts of hydrogen gas
15 while also being significant emitters of CO₂. Modern refineries, for example, utilize (on average) approximately 250 scf of H₂ per barrel of oil that is processed. Steam methane reforming (SMR), which is the main process currently being used for H₂ generation, has a CO₂ intensity of 24.5 kg-CO₂/kscf-H₂ which results in 6.1 kg-CO₂ being emitted per barrel of oil processed, this amount being attributed solely to the use of H₂ in hydrotreating/hydrocracking processes. The overall CO₂
20 emission per barrel is higher than this and ranges from 6.5-33 kg-CO₂/barrel of oil processed.

Much of the world's power is derived from the combustion of coal in steam cycle power plants. Methods of CO₂ removal from a power boiler include coal combustion with pure oxygen in an oxy-fuel burner diluted with recycle flue gas so that nitrogen is largely eliminated from the system and net CO₂ product derived from the coal can be produced for disposal. Alternatively the
25 stack gas can be treated with limestone slurry to remove sulfur dioxide followed by the removal of CO₂ from the stack gas using an amine chemical scrubbing process.

A further method of using coal or other solid or heavy liquid fuels such as refinery waste products or biomass is to gasify the fuels using pure oxygen in a partial oxidation reactor followed by gas treating to convert CO by reaction with steam in a catalytic reactor giving hydrogen and CO₂
30 then removal of CO₂ and sulfur compounds and other trace impurities giving a substantially pure hydrogen product for use as clean fuel in a combined cycle gas turbine power generation system.

A further method of power generation using natural gas, coal, refinery waste, or biomass fuel would involve the use of a closed cycle high pressure oxy-fuel power generation system using a working fluid, such as CO₂, N₂, Helium, H₂O, or the like. For example, systems utilizing N₂ as the

working fluid are described in US Pat. No. 9,410,481 and US Pat. No. 9,611,785, the disclosures of which are incorporated herein by reference.

In light of the significant amounts of CO₂ produced in various industrial gas streams, such as those exemplified above, there is a need for various processes for CO₂ removal from process streams. Separation and purification of carbon dioxide from industrial waste gas streams is a challenging process due to high energy and equipment costs. Currently, climate change due to global warming is an existential threat to humanity and release of significant amount of carbon dioxide to the atmosphere due to human activities (industry, transportation, residential, etc.) has been known as the main reason behind it. Thus, development of novel and efficient ways to capture and sequester or reuse the CO₂ emission from various industrial processes is of paramount importance. For example, global hydrogen generation capacity in 2017 was about 65M metric tons, and about 99% of that amount was produced through processes that release about 0.74 Gt /year of CO₂ into the atmosphere. This was more than 2% of overall global CO₂ emission in 2017 which was only due to hydrogen generation.

Known methods for removal of carbon dioxide from gas streams include absorption of carbon dioxide using a chemical solvent such as an amine solution or a physical solvent such as the Selexol™ process, separation using membrane diffusion, and separation using adsorption on a solid adsorbent, such as a zeolite or activated carbon. Fuel gas streams containing CO₂ are often burned releasing CO₂ into the atmosphere, and known methods for separation of CO₂ from gas streams are recognized as being prohibitively costly. Accordingly, there is a need for lower cost CO₂ removal systems which can easily be integrated into existing processes such as hydrogen generation, capable of 100% CO₂ recovery.

Hydrogen production systems using any hydrocarbon or carbonaceous fuel will in general require a large quantity of high temperature heat (e.g., about 500°C to about 1000°C) for feed preheating, and they produce large quantities of excess heat at low temperatures (e.g., about 200°C to about 400°C). Power stations have high grade heat available, and they can utilize low grade heat integrated into their systems. Because of the desirability of the use of hydrogen as a fuel source, there remains a need for means to provide hydrogen fuel at a low cost substantially without CO₂ emission to the atmosphere.

Previous efforts have been undertaken to provide for combined production of hydrogen and carbon dioxide, such as disclosed in U.S. Pat. No. 8,021,464. Such methods, however, are lacking in simplicity and cost efficiency. Accordingly, there remains a need for further systems and methods for removing carbon dioxide from process streams as well as simultaneously producing a valuable hydrogen stream.

SUMMARY OF THE INVENTION

The present disclosure relates to systems and methods for providing one or more streams of a substantially pure chemical compound, such as hydrogen and/or carbon dioxide. The disclosed systems and methods beneficially utilize an auto-refrigeration system that efficiently separated carbon dioxide from an industrial process stream at reduced cost. As such, in some embodiments, the present disclosure particularly can provide systems and methods for production of a carbon dioxide stream, specifically through separation of the carbon dioxide from an industrial stream including carbon dioxide and at least one further material. Such carbon dioxide separation can be particularly beneficial for use with systems and methods that produce a stream comprising hydrogen and carbon dioxide. Accordingly, in some embodiments, the present disclosure particularly can provide systems and methods for production of substantially pure hydrogen gas, such systems and methods include removal of carbon dioxide from a crude hydrogen product stream, such as through the auto-refrigeration methods described further herein.

Hydrogen production can comprise partially oxidizing or reacting a hydrocarbon fuel with oxygen in the presence of steam and or CO₂ to provide gaseous products that include and/or are converted into hydrogen. Moreover, because of the ability to efficiently remove CO₂ at a significantly reduced cost, the hydrogen can be produced with substantially zero CO₂ and other impurity emissions, and the hydrogen can be produced in a substantially pure form so that it can be utilized in a variety of manners, such as being use as a vehicle fuel, being used for power production or for heating, being used for production of fertilizer or other chemicals, or being used in oil refining.

In some embodiments the present disclosure can include the production of a mixture of H₂+CO using a single stage catalytic reactor with steam plus natural gas feeds, such as via steam methane reforming (SMR). Alternatively H₂+CO can be produced by the partial oxidation of a gaseous or liquid or solid hydrocarbon or carbonaceous fuel using pure oxygen (POX) or from a catalytic auto-thermal reactor (ATR) using a gaseous or liquid hydrocarbon fuel with O₂ plus steam feed. In some preferred embodiments, the present disclosure further can relate to systems and methods for generation of H₂+CO in a POX or ATR reactor followed by the use of a gas heated reformer (GHR) in either a series or parallel mode to the POX or ATR reactor to produce additional H₂ and CO (i.e., synthesis gas) by utilizing the exhaust sensible heat in the POX and/or ATR reactor system to provide the heat for endothermic catalytic steam plus hydrocarbon reforming reactions taking place in the GHR. As an example using natural gas fuel, the POX reactor has an exit temperature of about 1300°C to about 1450°C while an ATR reactor exit temperature is about

1000°C to about 1100°C. The outlet temperature of the GHR reactor is between 550°C and 650°C. The significantly lower exit temperature results in the an increase in the production of hydrogen of between 35% and 40% for a POX+GHR combination compared to a POX reactor alone, both systems using the same quantity of hydrocarbon feed and where the extra heat available from the POX product gas stream is used not for hydrogen production but to produce steam for power production in an associated power system. A further advantage of the two stage syngas production system is its ability to operate at syngas delivery pressures up to 100 bar with less than 5% unconverted methane from the feed hydrocarbon fuel present in the product syngas stream. System components suitable for carrying out a two stage syngas production method are described in US Pat. No. 9,327,972 and US Pat. No. 8,685,358, the disclosures of which are incorporated herein by reference. Hydrogen production should be maximized due to its much higher value compared to power production using excess steam.

The present disclosure further can provide for CO₂ capture in conventional H₂ systems, such as SMR. The state of art SMR system with CO₂ capture typically rely on the use of H₂-PSA waste gas as the fuel and the use of an AGR-based CO₂ separation unit on the exhaust of the SMR furnace. Such a system typically captures up to 90% of overall CO₂ from the process and produces H₂ that is about 45% more expensive than H₂ without CCS.

In one or more embodiments, the present systems and methods can utilize the unavoidable excess heat generated in the hydrogen plant (e.g., at a temperature level below 400°C) to provide additional heat input to other systems and methods that optionally may be combined with the hydrogen production system. For example, the excess heat from the hydrogen production can be added to a power production system and method to improve efficiency of such system and method. Hydrogen production systems commonly use a CO shift reactor to convert CO+H₂O to H₂+CO₂ with heat release so that in cooling the crude H₂ product stream to ambient temperature prior to purification there is a very large heat release at relatively low temperature level due to the sensible heat of the gas stream and the latent heat of condensation of the excess steam present which can ideally be used as an added heat source to other systems. Such added heat can be beneficial, as one example, to assist in achieving high electrical generation efficiency in a power production system.

In other embodiments, the present disclosure encompasses the provision of heat to the hydrogen production system. In particular, heat can be added to the hydrogen production system (e.g., at a temperature level of about 400°C to about 1000°C) and can be useful specifically for superheating one or both of a fuel stream (e.g., natural gas) and a steam feed stream to an H₂ + CO synthesis gas generation reactor system (e.g., any one or more of an SMR, a POX, an ATR, a POX+GHR, or an ATR+GHR). The added heat that is input to the hydrogen production system can

be provided from a variety of sources including, but not limited to, power production systems where high temperature combustion product streams are available.

In further embodiments, the hydrogen production system can include a steam generating boiler that can be useful for cooling the product gas from the H_2+CO reactor system and producing high pressure saturated steam, which can be superheated using high temperature heat derived from a different source. The superheated steam together with preheated hydrocarbon feed can then provide the feed to the H_2+CO reactor units. Any excess steam production can then be transferred to a further system. The H_2+CO syngas leaving the steam generating waste heat boiler (WHB) contains a substantial fraction of steam. It is then passed through a catalytic shift reactor where the steam combines with the CO in an endothermic reaction to produce H_2 and CO_2 . The crude hydrogen stream must be cooled to near ambient temperature from a typical high temperature level of about $400^\circ C$. The sensible heat rejected plus the additional heat produced from the condensation of the residual steam content produces a considerable excess heat release available after preheating H_2 reactor boiler feed water and reactor feed streams to a close temperature approach to the syngas stream leaving the steam generator. This excess heat can be transferred to a further system. Note that optionally a second lower temperature catalytic shift reactor can be used to maximize H_2 production. The present systems and methods can utilize a pressure swing adsorption (PSA) system to separate pure high pressure hydrogen from a cooled, crude hydrogen stream. The waste gas stream from the PSA unit at a pressure of about 1.2 bar to about 1.6 bar contains all the CO_2 produced from conversion of the hydrocarbon feed to H_2 together with CH_4+CO+H_2 , and it is saturated with water vapor.

In additional embodiments, the present disclosure can provide for the recovery of substantially all the carbon present in the fuel for the hydrogen plant as CO_2 , which can be compressed to pipeline pressure in the range of about 100 bar to about 200 bar for disposal. For example, this can be achieved by treating the ambient temperature crude H_2 stream in an amine CO_2 scrubbing system upstream of the PSA. The waste gas from the PSA can then be used as a minor portion of a fuel stream consumed in a combined or separate system. The disadvantage of the amine CO_2 removal system is its high capital cost and the large quantity of low pressure steam required for amine regeneration to produce the pure CO_2 product stream. The PSA waste gas stream contains a significant quantity of H_2+CO . The waste gas can be compressed, and with added steam, passed through a catalytic CO shift reactor which results in the cooled compressed waste gas stream having a H_2 molar concentration in the range of about 60% to about 85%. This stream can then be processed in a second PSA unit giving an additional H_2 production. This combination of amine scrubbing plus first stage PSA plus CO shift plus second stage PSA results in an overall ratio

of H_2 product divided by (H_2+CO) present in the syngas reactor product stream of greater than 95% and preferably greater than 97%. The hydrogen production system can preferably be configured so that a monoethanolamine (MEA) unit or a physical solvent CO_2 removal unit upstream of the first PSA is eliminated leaving all the CO_2 in the PSA waste gas stream.

5 Following compression and drying, this stream can be cooled to a temperature in the range of about $2^\circ C$ to about $10^\circ C$ above the CO_2 freezing temperature at which point the separation of the liquid phase and the vapor phase will result in greater than 70% and preferably greater than 80% of the CO_2 being removed as a liquid. Optionally the liquid CO_2 can be treated in a stripping distillation column to remove dissolved $H_2+CO+CH_4$ which will be transferred to the vapor phase.

10 The process is described in US Pat. No. 7,819,951, which is incorporated herein by reference. Other CO_2 removal systems including components that may be incorporated herein are disclosed in U.S. Pat. No. 8,021,464 and U.S. Pat. No. 8,257,476, the disclosures of which are incorporated herein by reference. The separated vapor stream which is within 2 bar of the waste gas compressor discharge pressure is then warmed to atmospheric temperature, optionally passed through a CO shift catalytic

15 reactor system with some added steam and treated as before in a second PSA unit which delivers H_2 at the same purity and pressure as the first PSA unit. A further preferred arrangement is to take the ambient temperature-gas stream separated from the bulk of the CO_2 , in the low temperature CO_2 removal system and recycle it back to the feed streams for the $H_2 + CO$ synthesis gas generation reactor. By closing the recycle loop completely, inert components can be vented from

20 the system, and this vented fuel gas stream can be consumed in a combined or separate system. The level of argon derived from the oxygen stream and nitrogen derived from both the hydrocarbon feed and the oxygen streams must be kept at a low total concentration of from 3% to 12% (molar) in the feed gas to the first PSA. This arrangement does not require a second CO shift and PSA system. All the hydrogen will be produced from the main PSA while all the CO_2 will be produced

25 from the low temperature CO_2 removal system.

 If desired, part or all of the oxygen used in the present systems and methods can be supplied from a cryogenic air separation plant or from a high temperature oxygen ion transport membrane (ITM) unit which has a low-pressure air feed. The oxygen can be produced from the ITM unit as a product O_2 gas stream or it can immediately react with a fuel gas such as natural gas mixed with a

30 suitable diluent such as CO_2 in an ITM oxy-fuel combustor or diluted with steam to produce H_2+CO syngas in an ITM reactor. The hydrogen plant can utilize a stream of high pressure gaseous oxygen at pressures up to 105 bar as feed to the $H_2 + CO$ synthesis gas generation reactor producing substantially pure H_2 at up to 95 bar from the PSA system. A cryogenic air separation plant supplying high pressure oxygen can be particularly useful to provide the oxygen.

In one or more embodiments, the hydrogen production system and method can be combined with a power production system and method in order to improve efficiency of both systems. For example, in some embodiments, a pulverized coal fired power station generating high pressure superheated steam for turbines has available in the convection section flue gas leaving the super-
5 heaters at temperatures in excess of 800°C. The feed streams of hydrocarbon gas and steam for the syngas generation reactors can be superheated to temperatures in the range 400°C to 600°C. The low level excess heat available from the H₂ production system can be used to heat part of the power station boiler feed water releasing steam which would normally be used for extra power production in the steam turbines. CO₂ removal in the power station would need to use either amine scrubbing
10 of the stack gas or the use of oxy-fuel coal combustion with recycle of flue gas followed by CO₂ purification based on established technology.

As a further example, a gas turbine combined cycle power generation system uses a hydrocarbon fuel, usually natural gas, which is burned in the gas turbine combustor. The fuel can be hydrogen which would generally be diluted with nitrogen or steam to reduce adiabatic flame
15 temperature. The integration with the hydrogen production system is particularly advantageous since it is possible not only for heat integration to take place but also for the hydrogen production to be sufficiently high to provide all the hydrogen fuel gas required by the gas turbine and also excess hydrogen for other uses. The integration not only increases efficiency but also eliminates near
20 100% of the CO₂ derived from combustion of the total hydrocarbon feed to the system. This is a very large improvement on the current system for CO₂ removal based on amine scrubbing of CO₂ from the gas turbine outlet stream. The syngas reactor feed streams can be preheated against the gas turbine exhaust which for an industrial unit is in the temperature range of about 500°C to about
620°C. The low temperature heat released from the hydrogen plant can be used for boiler feed-water preheating releasing steam for extra power production in the steam turbine.

In one or more embodiments, the present disclosure can provide a hydrogen production system that can be configured for integration with a further system that is configured to provide added heat to the hydrogen production system. In particular, the system can comprise: a CO+H₂ syngas reactor operating, for example, at up to 110 bar pressure with feed streams of hydrocarbon
25 fuel, steam, and optionally waste fuel gas plus CO₂, (preferably wherein the reactor system can comprise one or more of an SMR, a POX, an ATR, a POX+GHR, or an ATR+GHR); a waste heat boiler configured to cool syngas produced in the reactor system and produce saturated high pressure steam; a super-heater, which elevates the temperature of the reactor feed streams to a temperature in the range of about 400°C to about 600°C; one or more catalytic CO shift reactors, which convert CO by reaction with contained steam to produce H₂+CO₂; a heat exchanger system
30

configured to cool the syngas and condense excess steam, which provides heat required for preheating boiler feed water and optionally syngas reactor feed streams to a temperature of up to about 400°C; a first pressure swing H₂ purification unit (PSA) producing substantially pure H₂ product at a pressure within about 5 bar of the syngas reactor outlet pressure and a waste gas stream at a pressure of about 1.2 bar to about 1.6 bar; optionally a chemical or physical absorbent CO₂ removal system placed upstream of the first PSA unit; a compressor to compress the PSA waste gas stream to a pressure of about 2 bar to about 5 bar higher than the first PSA H₂ product stream; optionally a catalytic CO shift reactor system using added steam to convert CO in the compressed waste gas by reaction with steam to H₂+CO₂; a second PSA, which processes the waste gas stream which contains more than 60% molar H₂ concentration to produce a second substantially pure H₂ product stream at substantially the same pressure as the first H₂ product stream; and an outlet line for output of the waste fuel gas stream from the second PSA. In some embodiments, the system may include one or more lines for transfer of excess heat available from the syngas cooling duty and/or one or more lines for output of any excess steam or waste fuel gas from the H₂ production system. Optionally, the CO₂ removal system upstream of the first PSA unit may be eliminated. Further, optionally, the use of a CO₂ removal unit based on the principle of cooling the compressed and dried first PSA waste gas stream to within a temperature of 2°C to 10°C of the CO₂ freezing temperature and separating the liquid CO₂ from the residual waste gas stream with provision for purifying the CO₂ may also be eliminated. Also, optionally, the waste gas from the first PSA unit following waste gas compression and CO₂ removal can be recycled for use as part of the fuel gas feed to the syngas reactors. In order to prevent a build-up of inert argon plus nitrogen in the closed cycle loop according to such embodiments, there will be a purge gas stream taken conveniently upstream of the first PSA to limit the concentration of inerts to about 3% to about 12% (molar) concentration.

The integration of the hydrogen production system with a gas turbine combined cycle power generation system will, in addition to heat integration, use at least a portion of the produced hydrogen to provide all of the fuel gas required to power the gas turbine. The hydrogen will be suitably diluted with nitrogen derived from the cryogenic O₂ plant providing oxygen for the POX+GHR or the ATR+GHR syngas reactors and also, optionally, with excess heat and steam at a temperature level below 400°C derived from the hydrogen production system. This will result in the near 100% recovery of CO₂ derived from combustion of the total hydrocarbon feed to the H₂ production plus the power production systems.

In one or more embodiments, the present disclosure provides a simple and economic process to capture and purify CO₂ as a by-product from waste streams generated from various

processes such as oxy-fuel combustion and power generation, natural gas processing, and hydrogen generation. The systems and methods can be potentially utilized to purify and separate CO₂ from any industrial waste stream wherein an impure stream of CO₂ with at least 40 mol% CO₂ content exist or where lower concentration of CO₂ can be upgraded to at least 40 mol% concentration.

5 The presently discloses systems and methods can utilize known refrigeration methods to separate the contaminants in a process waste stream from CO₂. The present systems and methods, however, can utilize a unique arrangement of equipment that greatly simplifies the process and thus the cost of separation of purification of CO₂. The present systems and methods are particularly useful when integrated with a hydrogen production plant in which the hydrocarbon feed is
10 converted to H₂ + CO in a pressurized system by reaction with oxygen and steam and in which the process integration between the H₂ production and CO₂ removal units achieves substantially 100% CO₂ capture.

 In one or more embodiments, the present disclosure can be configured to generate a purified and clean CO₂ stream from a CO₂ containing process waste stream using refrigeration and
15 fractionation. Briefly, the impure CO₂ stream is cooled down to a temperature near the CO₂ triple point (-56.4 °C) to liquefy the CO₂ content followed by separation and purification in a mass transfer column. The process can be integrated with a pressurized hydrogen production system with internal transfer streams to achieve efficient low cost 100% CO₂ capture.

 In some embodiments, the present disclosure relates to a process for separating CO₂ from
20 contaminating components comprising methane, carbon monoxide, hydrogen, nitrogen, argon, oxygen, and water vapor characterized by a mass transfer separation column system for processing an impure liquid carbon dioxide stream at a temperature close to the freezing point of CO₂ to produce contaminant-enriched overhead vapor and carbon dioxide-enriched bottoms liquid product stream.

25 The separation column can have a reboiler for boiling a portion of the carbon dioxide-enriched bottoms liquid by indirect heat exchange against cooling impure carbon dioxide fluid to produce cooled impure carbon dioxide fluid for feeding and condensing said column system and warmed carbon dioxide-enriched fluid.

 The disclosed systems and methods can comprise a heat exchanger for further cooling
30 impure carbon dioxide fluid by indirect heat exchange to produce partially condensed impure carbon dioxide fluid.

 The discloses systems and methods can comprise a first pressure reduction arrangement for reducing the pressure of impure liquid carbon dioxide to produce reduced pressure impure liquid carbon dioxide which is within 10°C of the freezing point of the impure carbon dioxide liquid.

The discloses systems and methods can comprise further pressure reduction arrangements for expanding portions of the carbon dioxide enriched bottoms liquid to produce expanded carbon dioxide-enriched bottoms liquid streams at reduced pressure to be used as refrigerant streams to cool the impure carbon dioxide feed stream.

5 The impure carbon dioxide feed stream can be at least a portion of the waste gas stream from a first H₂ PSA train placed upstream of the CO₂ separation and purification step.

The pressure of the impure feed stream can be increased to give a CO₂ partial pressure of at least 15 bar.

10 At least a portion of the overhead vapor from the mass transfer column in the CO₂ separation system can be optionally compressed and recycled back to the H₂ plus CO syngas generation system of a pressurized hydrogen plant.

Overhead vapor from the mass transfer column can be optionally compressed and recycled back to a combined syngas generator equipment, comprised of a partial oxidation zone, a gas heated reformer zone, and waste heat boiler heat recovery heat exchanger.

15 The compressed overhead vapor from the separation column can be processed in a second H₂ PSA unit recovering at least 60 mol% of the H₂ in the separation column waste gas as a second H₂ product stream.

20 The CO₂ mass transfer column overhead vapor can be processed to catalytically react contained carbon monoxide with steam to produce additional hydrogen in a low temperature water-gas shift reactor to increase its H₂ content to at least 60% on a mole basis prior to the second H₂ PSA train.

At least a portion of the waste gas from the second H₂ PSA unit can be mixed with the waste gas from the first H₂ PSA and recycled back to the CO₂ separation train.

25 At least a portion of CO₂ separation train waste gas can be used as a fuel in a gas turbine, process heater, or an oxy-fuel burner.

At least a portion of the second H₂ PSA waste gas can be used as a fuel source for any purpose including in a gas turbine, process heater, an oxy-fuel burner, or the furnace of a steam methane reforming reactor (SMR).

30 In all cases, the produced CO₂ can be compressed to pipeline pressure for delivery to a suitable sequestration site.

In example embodiments, the present disclosure can provide a process for separating carbon dioxide (CO₂) from a process stream comprising CO₂ and one or more further components. In particular, the process can comprise: providing the process stream at a pressure such that a partial pressure of the CO₂ in the process stream is at least 15 bar; drying the process stream sufficiently

so that a dew point of the process stream comprising the CO₂ is reduced to a temperature of about -20°C or less; cooling the process stream in at least one heat exchanger to provide the process stream comprising the CO₂ as a two phase stream; expanding the two phase stream so as to reduce the temperature of the two phase stream to a temperature that is within about 15°C of a freezing point of the two phase stream; and separating the two phase stream to provide a vapor stream enriched with at least one of the one or more further components and to provide a liquid stream that is enriched with the CO₂. In one or more further embodiments, the process can be further characterized in relation to one or more of the following statements, which may be combined in any number and order.

The drying can comprise passage of the process stream comprising the CO₂ through a desiccant-packed bed.

The cooling can comprise cooling the process stream against at least a portion of the liquid stream that is enriched with the CO₂.

The cooling can comprise cooling the process stream in a first heat exchanger and in a second heat exchanger.

The cooling can comprise cooling the process stream in the first heat exchanger against a first portion of the liquid stream that is enriched with the CO₂ and cooling the process stream in the second heat exchanger against a second portion of the liquid stream that is enriched with the CO₂.

The process further can comprise expanding the first portion of the liquid stream that is enriched with the CO₂ and the second portion of the liquid stream that is enriched with the CO₂ so as to reduce the temperature of the first portion of the liquid stream that is enriched with the CO₂ and the second portion of the liquid stream that is enriched with the CO₂ prior to cooling the process stream in the first heat exchanger against the first portion of the liquid stream that is enriched with the CO₂ and cooling the process stream in the second heat exchanger against the second portion of the liquid stream that is enriched with the CO₂.

The first portion of the liquid stream that is enriched with the CO₂ and the second portion of the liquid stream that is enriched with the CO₂ can be separately expanded using separate valves.

The process further can comprise cooling the process stream in a reboiler heat exchanger.

The process further can comprise passing at least a portion of the liquid stream that is enriched with the CO₂ through the reboiler heat exchanger.

The cooling can comprise cooling the process stream against at least a portion of the vapor stream enriched with at least one of the one or more further components.

The process can comprise expanding the two phase stream so as to reduce the temperature of the two phase stream to a temperature that is within about 10°C or about 5°C of the freezing point of the two phase stream.

5 The separating the two phase stream can comprise passing the two phase stream through a distillation column.

The distillation column can include a stripping section below a feed point of the two phase stream into the distillation column and includes a rectifying section above the feed point of the two phase stream into the distillation column.

10 The process can comprise separating the liquid stream that is enriched with the CO₂ into a first liquid CO₂ stream, a second liquid CO₂ stream, and a third liquid CO₂ stream.

The process can comprise independently expanding one, two, or three of the first liquid CO₂ stream, the second liquid CO₂ stream, and the third liquid CO₂ stream so as to reduce a temperature thereof and form a refrigerant stream.

15 The process can comprise compressing one, two, or three of the first liquid CO₂ stream, the second liquid CO₂ stream, and the third liquid CO₂ stream.

The process can comprise compressing the vapor stream enriched with at least one of the one or more further components.

The one or more further components can be one or more of a hydrocarbon, carbon monoxide, hydrogen, nitrogen, argon, and water vapor.

20 The process can comprise expanding the vapor stream enriched with at least one of the one or more further components so as to reduce a temperature thereof and form a refrigerant stream.

The process can comprise passing at least a portion of the vapor stream enriched with at least one of the one or more further components through a pressure swing absorber unit.

25 The passing can be effective to recover at least 60 mol% or at least 75 mol% of any H₂ present in the vapor stream enriched with at least one of the one or more further components.

30 The process can comprise recycling at least a portion of the vapor stream enriched with at least one of the one or more further components for combination with the process stream prior to said drying step. For example, at least a portion of the waste gas from the low temperature CO₂ removal system and/or a second PSA can be recycled back to a GHR in a hydrogen production process. As another example, at least a portion of the waste gas from the low temperature CO₂ removal system and/or a second PSA can be recycled back to a POX reactor in a hydrogen production process. As still another example, at least a portion of the waste gas from the low temperature CO₂ removal system and/or a second PSA can be recycled back to a combined reactor in a hydrogen production process. Such combined reactor can be a reactor unit that is a combined

pressure vessel comprised of a partial oxidation zone at the bottom, a gas heated reformer zone with open-ended tubes in the middle, and a waste heat boiler heat exchanger at the top. In such configuration, a single combined syngas stream and superheated steam can be main products leaving the pressure vessel.

5 The process stream can be an H_2+CO_2 stream from a hydrogen production process.

The process can be carried out without using an external refrigerant.

10 In example embodiments, the present disclosure particularly can provide a carbon dioxide (CO_2) separation system. In particular, such system can comprise: a compressor configured for compressing a process stream, wherein the process stream comprises CO_2 and one or more further components; a drier configured for removing moisture from the process stream; at least one heat exchanger configured for cooling the process stream against one or more cooling streams and providing the process stream as a two-phase stream; at least one expander configured for cooling the two-phase stream via expansion of the two-phase stream; and a mass transfer column configured to receive the two phase stream and generate a vapor phase stream and a liquid phase stream.

15 In example embodiments, the present disclosure can provide a hydrogen production system. In particular, such hydrogen production system can comprise: a reactor unit configured for receiving a hydrocarbon feed stream and oxygen and forming a product gas stream comprising H_2+CO ; a steam generating boiler configured for cooling the product gas stream comprising H_2+CO and for forming steam; at least one reactor configured for receiving the product gas stream comprising H_2+CO and providing a stream comprising H_2+CO_2 ; a pressure swing adsorber configured to receive the stream comprising H_2+CO_2 and provide a product stream formed of substantially pure hydrogen and also provide waste gas stream comprising CO_2 ; a compressor configured for compressing the waste gas stream comprising the CO_2 ; a drier configured for removing moisture from the waste gas stream comprising the CO_2 ; at least one heat exchanger configured for cooling the waste gas stream comprising the CO_2 against one or more cooling streams and providing the waste gas stream comprising the CO_2 as a two-phase stream; at least one expander configured for cooling the two-phase stream via expansion of the two-phase stream; and a separator configured for separating the two-phase stream into a vapor phase stream and a liquid phase stream. In further embodiments, the hydrogen production system can be characterized in relation to one or more of the following statements, which statements can be combined in any number and order.

The hydrogen production system further can comprise one or more heat exchangers configured for heating the hydrocarbon feed stream against one or both of the product gas stream comprising H_2+CO and the stream comprising H_2+CO_2 .

5 The hydrogen production system further can comprise one or more heat exchangers configured for transfer of excess heat to an external process.

The hydrogen production system further can comprise one or more lines configured for output of one or both of a waste fuel gas stream and steam generated in the hydrogen production system.

10 The hydrogen production system further can comprise one or more lines configured for delivery of at least part of the product stream formed of substantially pure hydrogen as fuel to a gas turbine.

The reactor unit can comprise a steam plus hydrocarbon plus optionally CO_2 catalytic reformer.

The reactor unit can comprise a partial oxidation unit.

15 The reactor unit can comprise a catalytic auto-thermal reformer.

The reactor unit can comprise a first stage unit that is either an auto-thermal reformer or a partial oxidation reactor and comprises a second stage gas heated steam plus hydrocarbon catalytic reformer.

20 At least part of the H_2+CO stream produced from the reactor unit can be generated in an ITM partial oxidation reactor using a low pressure preheated feed air stream air stream.

The hydrogen production system of further can comprise a super-heater heat exchanger configured to transfer heat from an external heat source to at least the hydrocarbon feed stream.

The reactor unit can be a combined pressure vessel comprised of a partial oxidation zone and a gas heated reformer.

25 The partial oxidation zone can be at a bottom portion of the combined pressure vessel, and the gas heated reformer can comprise open-ended tubes in a middle zone of the combined pressure vessel and a waste heat boiler heat exchanger at a top portion of the combined pressure vessel.

30 In example embodiments, the present disclosure can provide a process for hydrogen production. In particular, the process can comprise: reacting a hydrocarbon feed stream and oxygen into a reactor unit to form a product gas stream comprising H_2+CO ; passing the product gas stream comprising H_2+CO through a steam generating boiler to add steam to the product gas stream comprising H_2+CO ; converting the product gas stream comprising H_2+CO in at least one reactor to form a stream comprising H_2+CO_2 ; processing the stream comprising H_2+CO_2 in a pressure swing adsorber to provide a product stream formed of substantially pure hydrogen and also provide waste

gas stream comprising CO₂; forming a liquid CO₂ product stream in a cryogenic separation unit operating with auto-refrigeration by passing the waste gas stream comprising CO₂ therethrough such that at least 50 mol% of the CO₂ in the waste gas stream comprising CO₂ is separated into the liquid CO₂ product stream; and recycling a vapor phase stream from the cryogenic separation unit.

5 In further embodiments, the process can be characterized in relation to one or more of the following statements, which can be combined in any number and order.

The cryogenic separation unit operating with auto-refrigeration can operate without using an external refrigerant.

10 The cryogenic separation unit can comprise: a drier configured for removing moisture from the waste gas stream comprising CO₂; at least one heat exchanger configured for cooling the waste gas stream comprising CO₂ against one or more cooling streams and providing the waste gas stream comprising CO₂ as a two-phase stream; and at least one expander configured for cooling the two-phase stream via expansion of the two-phase stream.

15 The cryogenic separation unit further can comprise: a compressor configured for compressing the waste gas stream comprising CO₂, the compressor being positioned upstream from the drier; and a separator configured for separating the two-phase stream into the vapor phase stream and the liquid CO₂ product stream.

The process can comprise removing CO₂ from the stream comprising H₂+CO₂ prior to processing the stream comprising H₂+CO₂ in the pressure swing adsorber.

20 The removing of CO₂ from the stream comprising H₂+CO₂ can comprise passing the removing CO₂ from the stream comprising H₂+CO₂ through a chemical or physical solvent based CO₂ removal unit.

A portion of the waste gas stream comprising CO₂ exiting the pressure swing adsorber can be compressed and recycled back to the reactor unit.

25 At least a portion of the vapor phase stream from the cryogenic separation unit can be recycled back to the reactor unit.

The vapor phase stream from the cryogenic separation unit can be processed through a second pressure swing absorber to remove at least a portion of any H₂ present in the vapor phase stream prior to recycling of the vapor phase stream from the cryogenic separation unit.

30 The process can comprise removing at least a portion of any argon and nitrogen present in one or both of the product gas stream comprising H₂+CO and the stream comprising H₂+CO₂ prior to entry of the stream comprising H₂+CO₂ into the pressure swing absorber such that the total concentration of argon and nitrogen in the stream comprising H₂+CO₂ at an inlet of the pressure swing adsorber in the range of about 3 mol% to about 12 mol%.

At least 80 mol% of the CO₂ in the waste gas stream comprising CO₂ can be separated into the liquid CO₂ product stream.

The forming of the liquid CO₂ product stream in the cryogenic separation unit can comprise: providing the waste gas stream comprising CO₂ at a pressure such that a partial pressure
5 of the CO₂ in the process stream is at least 15 bar; drying the waste gas stream comprising CO₂ sufficiently so that a dew point of the waste gas stream comprising CO₂ is reduced to a temperature of about -20°C or less; cooling the waste gas stream comprising CO₂ in at least one heat exchanger to provide the waste gas stream comprising CO₂ as a two phase stream; expanding the two phase
10 stream so as to reduce the temperature of the two phase stream to a temperature that is within about 15°C of a freezing point of the two phase stream; and separating the two phase stream to provide the vapor phase stream and to provide the liquid CO₂ product stream.

The vapor phase stream from the cryogenic separation unit can be passed through a catalytic CO shift unit with an economizer heat exchanger, has steam added thereto, and is then passed through a catalytic reactor to convert at least a portion of the contained CO by reaction with the
15 steam to form a further stream comprising H₂+CO₂ and to form a gas stream containing at least 60 mol% H₂.

BRIEF DESCRIPTION OF THE DRAWINGS

Having thus described the disclosure in the foregoing general terms, reference will now be
20 made to the accompanying drawings, which are not necessarily drawn to scale, and wherein:

FIG. 1 is a flow diagram of a low temperature separation unit according to embodiments of the present disclosure useful for separation of carbon dioxide from a process stream utilizing auto-refrigeration.

FIG. 2 is a flow diagram of a hydrogen production facility including a low temperature
25 carbon dioxide separation unit according to embodiments of the present disclosure.

DETAILED DESCRIPTION

The present subject matter will now be described more fully hereinafter with reference to exemplary embodiments thereof. These exemplary embodiments are described so that this
30 disclosure will be thorough and complete, and will fully convey the scope of the subject matter to those skilled in the art. Indeed, the subject matter can be embodied in many different forms and should not be construed as limited to the embodiments set forth herein; rather, these embodiments are provided so that this disclosure will satisfy applicable legal requirements. As used in the

specification, and in the appended claims, the singular forms “a”, “an”, “the”, include plural referents unless the context clearly dictates otherwise.

The present disclosure provides systems and methods for production of various materials that are typically gaseous at standard temperature and pressure (e.g., about 20 °C and about 1 bar).

5 The systems and methods are particularly suitable for production of hydrogen and/or carbon dioxide. In one or more embodiments, the systems and methods can relate to the production of hydrogen alone or in combination with carbon dioxide. Likewise, the systems and methods can relate to the production of carbon dioxide that is separated from a process stream, and such separation can also relate to production of hydrogen. In some embodiments, the present systems
10 and methods relate to processes useful in separating carbon dioxide from a process stream that may or may not include hydrogen. In specific embodiments, the systems and methods relate to the production of hydrogen and production of carbon dioxide and can include producing a stream comprising both of hydrogen and carbon dioxide and separating the carbon dioxide from the hydrogen to provide a substantially pure stream of hydrogen and a substantially pure stream of
15 carbon dioxide.

In one or more embodiments, the present disclosure relates to systems and methods suitable for separation of carbon dioxide from a process stream. The process stream may be any industrial process stream comprising carbon dioxide. In some embodiments, the process stream may be a stream from a hydrogen production process. In other embodiments, the process stream may be any
20 further industrial process stream comprising carbon dioxide wherein it can be beneficial to separate at least a portion of the carbon dioxide therefrom. For example, referring to FIG. 2, the process stream may be any of streams 308, 331, and 309. As such, the carbon dioxide separation process may be combined with a hydrogen production process as described herein, or the carbon dioxide separation process may be utilized with a different process stream.

25 A simplified block flow diagram of a carbon dioxide separation process according to the present disclosure is shown in FIG. 1. As seen therein, a process stream 101 containing CO₂ is provided. As noted above, the process stream 101 may be received from any source, such as a hydrogen production process. The process stream 101 can be compressed to a pressure of at least 30 bar, at least 35 bar, or at least 40 bar (e.g., to a maximum of 100 bar) within a compressor 200.
30 In example embodiments, the compressor 200 may be an intercooled multi-stage compressor. The compression step preferably will raise the partial pressure of the CO₂ within the waste stream to at least about 15 bar (e.g., up to a maximum, in some embodiments, of about 55 bar). The CO₂ partial pressure can be raised to be in the range of about 15 bar to about 55 bar, about 15 bar to about 45 bar, or about 15 bar to about 40 bar. The compressed process stream 102 is then directed to a drier

205 to reduce the moisture content of the compressed process stream and form a first impure CO₂ stream 103. The extent of moisture removal can be adjusted as desired such that the dew point of the process stream will be reduced to a temperature as low as about -60°C. In various embodiments, the dew point can be reduced to a temperature of about -10°C or less, about -20°C or less, or about -40°C or less, such as to a low temperature of about -60°C. For example, the dew point can be reduced to a temperature in the range of about -60°C to about -10°C, about -60°C to about -20°C, or about -60°C to about -30°C. The drier 205, in some example embodiments, can be a drying bed packed with appropriate desiccant material, such as molecular sieves or zeolites.

The first impure CO₂ stream 103 is cooled to significantly reduce the temperature thereof and ultimately form a two phase stream that is then subject to rapid cooling utilizing auto-refrigeration. In some embodiments, auto-refrigeration can generally indicate that the refrigeration is carried out in the express absence of any external refrigerant. In other words, the streams are not cooled against a typical refrigerant stream, such as Freon, liquid nitrogen, liquid propane, ammonia, or the like. Rather, the stream is only cooled against further streams produced in the CO₂ separation process and using expansion techniques. In particular, auto-refrigeration can indicate that at least one stream comprising a liquid component is expanded to provide for rapid cooling of the stream.

Returning to FIG. 1, the first impure CO₂ stream 103 is directed to a first heat exchanger 210 to partially cool down and form the second impure CO₂ stream 104. Thereafter, the second impure CO₂ stream 104 is directed to a reboiler heat exchanger 215 to further cool down and form the third impure CO₂ stream 105. The third impure CO₂ stream 105 is further cooled down in a second heat exchanger 211 to form a fourth impure CO₂ stream 106. The foregoing cooling steps can be effective to provide the impure CO₂ stream(s) in the form of a two phase stream including a gaseous component and a liquid component. In some embodiments, the two phase stream is at least partially formed during passage through the reboiler heat exchanger 215 and/or is formed during passage through the second heat exchanger 211.

To further facilitate cooling of the impure CO₂ stream, the fourth impure CO₂ stream 106 is expanded within a first valve 220 to an appropriate pressure that would drop the temperature of the expanded impure CO₂ stream 107 to near the CO₂ triple point temperature (-56.4° C). For example, expansion of the stream 106 can be effective to reduce the temperature of the stream to within about 15°C, within about 10°C, or within about 5°C of the freezing point of the CO₂ in the stream. A cold, two phase CO₂ stream 107 thus exits the first valve 220.

The cold two phase CO₂ stream 107 becomes a feed stream to the mass transfer column 225. The mass transfer column 225 has a stripping section 226 below the feed point of stream 107

producing a high purity liquid CO₂ stream 108 as a bottom product and a rectifying section 227 above the feed point of stream 107 producing a purified top vapor phase product 109. The mass transfer column 225 is packed with appropriate packing material to enhance the mass transfer within the column and collection of the liquid CO₂ at high purity. The design of the stripping column will be done such that it can effectively handle the two-phase feed stream which could be done in variety of ways such as but not limited to flashing the feed in a flash vessel prior to the entrance to the stripping column, the use of a gallery tray or chimney tray within the column or any combination of thereof. The bottom liquid CO₂ product 108 typically contains about 80 mol% and preferably at least 85 mol% of the total CO₂ within the impure CO₂ stream 107 while the rest of the CO₂ content and other volatile impurities within the feed waste stream would end up in the overhead vapor phase stream 109. In various embodiments, the bottom liquid CO₂ product 108 can contain at least 50 mol%, at least 60 mol%, at least 70 mol%, or at least 80 mol% (e.g., about 50 mol% to about 99 mol%, about 60 mol% to about 98 mol%, about 70 mol% to about 95 mol%, or about 75 mol% to about 90 mol%) of the total CO₂ within the cold two phase CO₂ stream 107. The bottom liquid CO₂ product 108 passes through the reboiler heat exchanger for further cooling and exits as purified a CO₂ product stream that splits into a first portion 110 and a second portion 150, which is recycled back into the bottom section of the mass transfer column 225.

The cool overhead vapor phase stream 109 can be used as a source of refrigeration to cool down the impure CO₂ streams in heat exchangers 210 and 211. These two heat exchangers are preferably plate and fin type made from aluminum and although they are shown as discrete blocks in FIG. 1, they may be designed and fabricated as a single unit with two (or more) sub-unit or sections. The system is suitably insulated. The liquid CO₂ product 108 preferably is at least 80% molar pure CO₂, at least 85% molar pure CO₂, at least 90% molar pure CO₂, at least 95% molar pure CO₂, at least 98% molar pure CO₂, at least 99% molar pure CO₂, at least 99.5% molar pure CO₂, or at least 99% molar pure CO₂.

To generate additional refrigeration duty, the purified CO₂ product stream portion 110 exiting the reboiler heat exchanger 215 can be divided into 3 separate streams 111, 114, and 117. Purified CO₂ product streams 111 and 114 can be reduced in pressure by expansion in valves 230 and 235, respectively, to achieve appropriate temperature profiles in heat exchangers 210 and 211. Specifically, purified CO₂ product stream 111 exits valve 230 as stream 112 and passes through heat exchanger 211 to provide purified CO₂ stream 113. Similarly, purified CO₂ product stream 114 exits valve 235 as stream 115 and passes through heat exchanger 210 to provide purified CO₂ stream 116. Although each of streams 112 and 115 are illustrated as passing through only one of heat exchangers 210 and 211, it is understood that one or both of streams 112 and 115 may be

passed through both of heat exchangers 210 and 211 prior to passing to the compression step described next. The purified CO₂ streams (113, 116 and 117) will be partially pressurized and mixed within a compressor 240 to form a high density CO₂ stream 118 before being raised in pressure to the required end-use pressure in a liquid pump 245 to leave as final CO₂ product stream 119. The final warm overhead vapor phase stream 109 can be optionally compressed based on the downstream application requirement.

An important feature of this arrangement is the capability of recycling the vapor phase stream 109 from the separation column 225 after warming in heat exchanger 211 to form stream 120 and heating in heat exchanger 210 to form stream 121 at near ambient temperature. The stream 121 can be compressed in compressor 250 to form stream 122. The stream 122 can be at least partially combined with original feed stream 101, and this recycle allows for a favorable increase in the overall CO₂ recovery from the process feed stream 101. Furthermore, the stream 122 can be partially or completely recycled back as the feedstock to a chemical production process (such as a hydrogen production process further described below) and achieve up to 100% CO₂ capture from the chemical production process.

In example embodiments, the presently disclosed systems and methods for carbon dioxide separation particularly can be useful with hydrogen generation processes or revamping of existing hydrogen generation processes that utilize only one H₂ separation train such as PSA beds or membrane separators to achieve 100% CO₂ capture. Current methods of thermochemical hydrogen generation typically rely on recovery of hydrogen using PSA beds. Specifically, natural gas and steam (and optionally oxygen) can be input to an H₂+CO syngas generation area along with a PSA waste gas. The product therefrom is subjected to syngas cooling and shifting of the CO to H₂. Thereafter, PSA separation is carried out to provide an H₂ product and the PSA waste gas. The PSAs recover 75% to 90% of the total hydrogen in the feed gas. The PSA waste gas containing typically 10% to 15% of the hydrogen production together with all the CO₂ produced from H₂ generation is generally burned with CO₂ vented to the atmosphere.

The systems and methods of the present disclosure can be utilized to capture substantially 100% of the CO₂ from hydrogen generating processes by recovering CO₂ from a pressure swing absorber (PSA) waste stream. This can encompass, for example, utilizing a CO₂ separation process as described above in combination with a hydrogen production process as will be described below. Separation of CO₂ from PSA off-gas increases the hydrogen concentration in CO₂ separation train waste gas to at least about 60 mol% which would make it suitable and economic for additional H₂ recovery within a second PSA. In addition, based on the concentration of CO within CO₂ separation train waste gas, it can be optionally shifted, prior to the second H₂ recovery step, using a

small low temperature shift reactor to further increase its hydrogen content. The off-gas from the second PSA unit will be recycled back to the syngas generation reactors. It can also be optionally mixed with the off-gas from the first PSA to increase CO₂ recovery in the CO₂ cryogenic separation system.

5 Previous efforts have been undertaken to provide for production of hydrogen through combination with additional systems, and one or more elements from such previous endeavors may be integrated into the presently disclosed systems and methods. For example, US Pat. No. 6,534,551, the disclosure of which is incorporated herein by reference, describes the combination of: 1) a hydrocarbon fuel gas reaction with steam and or oxygen; and 2) a power system utilizing a
10 compressed oxidant gas in which a fuel gas is burned with combustor products producing power by work expansion and in which the expanded combustion product gas is used to superheat the steam used in hydrogen synthesis reactions and in which the oxygen production unit is driven by at least a portion of the power produced by the expansion of the combustion product gas.

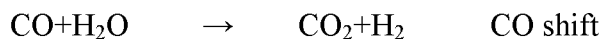
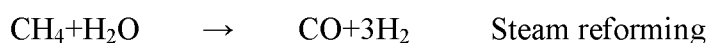
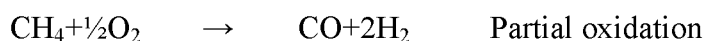
In one or more embodiments, the present systems and methods can beneficially provide for
15 hydrogen production with capture of substantially all of the carbon produced, particularly substantially all of the CO₂ produced. In this manner, the present disclosure may refer to a hydrogen plant, and it is understood that such hydrogen plant refers to the combination of elements necessary to form the hydrogen production system utilized herein. A hydrogen plant as described herein thus can be configured for producing substantially pure hydrogen and likewise producing
20 substantially pure carbon dioxide that is separated from a crude hydrogen stream.

A hydrogen production plant for use according to the present disclosure can incorporate any variety of elements known to be suitable in prior hydrogen production plants. In particular, the hydrogen production plant can comprise a reactor unit configured for forming a stream comprising CO+H₂ gas. The reactor unit can encompass a single element or a plurality of elements. For
25 example, a reactor unit in a hydrogen production plant can comprise a two stage reactor unit including a first stage reactor which converts a hydrocarbon feed to a CO+H₂ gas. Such so-called H₂ + CO synthesis gas generation reactor can be any one or more of a steam methane reforming (SMR) reactor, a partial oxidation (POX) reactor, an autothermal reforming (ATR) reactor, a POX+GHR (gas heated reactor), or an ATR+GHR. In some embodiments, partial oxidation of a
30 natural gas feed with pure oxygen can be carried out at an outlet temperature of about 1300°C to about 1500°C at typical pressures of about 30 bar to about 150 bar. An auto-thermal reformer can add steam and excess hydrocarbon, generally natural gas, after the partial oxidation burner so that the high temperature gases can then pass through a bed of catalyst where subsequent steam-hydrocarbon reforming reactions take place yielding further H₂+CO and cooling the gas mixture to

an outlet temperature of about 1000°C to about 1100°C at pressures of about 30 bar to about 150 bar. The second stage reactor can comprise a steam/hydrocarbon catalytic reformer in which the total H₂+CO gas product from both reactors (e.g., at a temperature of about 1000°C or greater) is used to provide the endothermic heat of the reforming reactions in a convectively heated shell side flow with catalyst in the tubes. Optionally the two reactors can operate in a series or parallel mode. A favorable configuration uses a vertical gas heated reformer (GHR) with catalyst filled open ended tubes hanging from a single tube sheet at the top of the vessel, with the product H₂+CO leaving the reformer tubes and mixing with the product gas from a POX reactor or an ATR in the base of the GHR, and the total product H₂+CO stream passing through the shell side and cooling typically from about 1050°C to 550°C to 800°C.

An advantage of the two reactor configuration is that the yield of H₂+CO from hydrocarbon feed is maximized, and all CO₂ formed in the reactions is contained within the high-pressure system. The product CO+H₂ gas is further cooled in a steam generating waste heat boiler (WHB), and a further advantage is that this steam quantity is only sufficient to provide the required steam flow to the two H₂+CO reactors with only a small excess flow. The system has no large by-product steam production.

To generate hydrogen, the H₂+CO product leaving the WHB at a typical temperature of about 240°C to about 290°C and containing typically about 20 mol% to about 40 mol% steam is passed through either one or two (or more) catalytic shift converters where CO reacts with steam to produce CO₂ and more H₂. The reactions for the whole H₂ production process sequence are shown below (using CH₄ as the hydrocarbon).



The total CO+H₂ product passing through the CO shift reactors is cooled, and a significant amount of heat is released generally at a temperature level of up to 400°C or lower as the gas cools and steam condenses. This heat is released not at a single temperature level but over a temperature range down to near ambient temperature. Part of this heat release can be used to preheat boiler feed

water, to produce the steam required for syngas production in the reactors but there is a large excess quantity that is at a low temperature level and only available over a temperature range.

The efficiency of the H_2+CO generation in the two reactors can be significantly increased by preheating the hydrocarbon and steam feeds to typically about $400^{\circ}C$ to about $600^{\circ}C$ and preferably to about $500^{\circ}C$ to about $550^{\circ}C$. This preferably is done using an external heat source since no excess heat at these temperature levels is available within the H_2+CO generation reactors plus WHB.

In one or more embodiments, systems and methods of producing the H_2+CO syngas which can be used to produce the pure hydrogen product stream according to the present disclosure may exhibit desired characteristics that can be beneficial for integration of the hydrogen production with other systems, such as power generation systems. The excess heat available over a temperature range from near ambient up to about $400^{\circ}C$ is ideal for boiler feed water heating in a steam based power cycle or for heating a high pressure CO_2 stream. In each case the result is a reduction in parasitic power demand and an increase in power cycle efficiency. The required external heat need to preheat the syngas reactor feed streams up to about $550^{\circ}C$ can easily be provided using high temperature boiler flue gas leaving the super-heater in a pulverized coal fired power boiler or using the hot turbine exhaust from an industrial gas turbine in a combined cycle power generation system or using a further high temperature exhaust stream from a power production system. The heat integration leads to an overall increase in the efficiency of a combined system.

The cooled H_2 rich gas stream is now passed through an ambient cooler where condensed water is removed. The gas stream is then passed through a conventional multi-bed pressure swing adsorber (PSA) which separates typically about 85% to about 90% of the hydrogen as a pure stream having typically about 10 ppm to about 50 ppm total impurities. All the impurities in the crude H_2 feed stream are separated as a waste fuel gas stream, which waste stream can comprise any combination of components, such as H_2 , CO , CO_2 , CH_4 , N_2 , Ar , and a small quantity of vapor phase H_2O . The pressure is typically about 1.1 bar to about 1.6 bar. This waste gas typically has about 20% of the total hydrocarbon reactor hydrocarbon feed lower heating value (LHV) so its efficient use is critical to the overall economics of H_2 production. The waste gas contains all the carbon from the total hydrocarbon feed as CO_2+CO and the recovery of this carbon as pure CO_2 at pipeline high pressure is vital to meet climate change emission objectives. In order to recover the carbon present in the hydrocarbon feed to the hydrogen plant as CO_2 product the ideal objective is to convert residual CO by catalytic shift reaction with added steam to produce CO_2+H_2 then separate the CO_2 as a pure product stream. Three options are available which address this problem of CO_2 removal and the maximization of CO_2 recovery.

In some embodiments, CO₂ removal and the maximization of CO₂ recovery can comprise adding a chemical or physical solvent scrubbing unit to remove all the CO₂ from the ambient temperature PSA feed stream. For example, this can be achieved by treating the ambient temperature crude H₂ stream in an amine CO₂ scrubbing system upstream of the PSA. The waste gas from the PSA can then be used as a minor portion of the fuel stream consumed in the power system. The PSA waste gas stream contains a significant quantity of H₂+CO. Alternatively, the waste gas stream can be compressed to a pressure of 1 to 2 bar higher than the H₂ delivery pressure from the PSA and then passing this gas stream with added steam through a catalytic CO shift conversion unit which would convert over 90% of the CO by reaction with steam to CO₂+H₂. The cooled product gas stream will now have a hydrogen concentration of 60% to 70% (molar). This gas stream can then be passed through a second multi-bed pressure swing adsorption unit to recover an additional H₂ product stream at the same pressure and purity as the hydrogen from the first PSA. The waste gas from the second PSA unit which contains all the inert argon and nitrogen derived from the hydrocarbon and oxygen reactor feed streams can beneficially be sent to the power plant for combustion. The disadvantage of the amine CO₂ removal system is its high capital cost and the large quantity of low pressure steam required for amine regeneration to produce the pure CO₂ product stream. This combination of amine scrubbing plus first stage PSA plus CO shift plus second stage PSA results in an overall ratio of H₂ product divided by (H₂+CO) present in the syngas reactor product stream of greater than 95% and preferably greater than 97%.

In other embodiments, CO₂ removal and the maximization of CO₂ recovery can comprise eliminating the MEA unit or the physical solvent CO₂ removal unit upstream of the first PSA leaving all the CO₂ in the PSA waste gas stream. The stream then can be treated utilizing cryogenic cooling for separation of the CO₂ as otherwise described herein.

In further embodiments, CO₂ removal and the maximization of CO₂ recovery can comprise recycling one or more streams back to the feed streams for the POX or ATR or GHR or SMR reactors. By closing the recycle loop completely, inert components can be vented from the system. The vented purge gas stream can be taken at ambient temperature upstream of the first PSA and sent, for example, to a power plant for combustion. The level of argon present in the oxygen stream and nitrogen present in both the hydrocarbon feed and the oxygen streams are preferably kept at a low total concentration of from about 3 mol% to about 12 mol% in the feed gas to the first PSA. This arrangement does not require a second CO shift and PSA system. All the hydrogen will be produced from the main PSA while all the CO₂ will be produced from the low temperature CO₂ removal system. As further described herein, CO₂ separation can be applied independent of the

hydrogen production processes described herein. Suitable CO₂ separations systems and methods are thus described herein that may be applied to any process stream comprising CO₂.

Example embodiments of a hydrogen production plant (and an associated hydrogen production process) are evident in relation to FIG. 2. The hydrogen plant can be fueled with a hydrocarbon fuel source, preferably a gaseous hydrocarbon, and more preferably with substantially pure methane. The example embodiment of FIG. 2 is described in relation to the use of methane as the hydrocarbon. In FIG. 2, the methane in stream 300 is compressed in compressor 401 to a pressure of about 20 bar to about 120 bar, about 40 bar to about 110 bar, or about 60 bar to about 100 bar. The compressed methane stream is passed through a heat exchanger 412 to heat the methane stream to a temperature of about 300°C to about 700 °C, about 350°C to about 650°C, or about 400°C to about 600°C. The methane exiting the heat exchanger 412 is split into two streams 302 and 303. The methane is thus directed to a reactor unit that, as exemplified in FIG. 2, is formed of a POX reactor 402 and a GHR 403. In other embodiments, it is understood that the reactor unit may be formed of a single device or multiple devices as otherwise already discussed herein. The methane in stream 302 combined in the POX reactor with an oxygen stream 301 that is pre-heated in heater 418 prior to passage into the POX reactor. Preferably, the oxygen stream 301 can be about 99.5% pure O₂ and can be taken, for example, from a cryogenic air separation plant (not illustrated). The oxygen entering the POX reactor 302 may be at a pressure in the range of about 20 bar to about 120 bar, about 40 bar to about 110 bar, or about 60 bar to about 100 bar.

The methane is partially oxidized in the POX reactor 302 with the oxygen to produce a product H₂+CO stream 330 at a temperature of about 700°C to about 1800°C, about 900°C to about 1700°C, or about 1100°C to about 1600°C. The product H₂+CO stream 330 optionally be quenched and cooled by the addition of a quenching stream, such as to a temperature that is about 50°C or more, about 75°C or more, or about 100°C or more below the temperature of the product H₂+CO stream 330 directly exiting the POX reactor 402. The optionally quenched product H₂+CO stream 330 enters the base of the GHR reactor 403, undergoes endothermic reforming reactions, and leaves the GHR as stream 304. The total product CO+H₂ stream can exit the GHR 304 at a temperature of about 300°C to about 900°C, about 400°C to about 800°C, or about 500°C to about 700°C. The total product CO+H₂ stream 304 passes through the waste heat boiler 404 and exits in stream 305 at a temperature in a range of about 150°C to about 450°C, about 200°C to about 425°C, or about 250°C to about 400°C. The waste heat boiler can be a steam generating boiler and thus can be effective to add steam to the total product CO+H₂ stream.

The product stream comprising H₂+CO is then reacted in at least one reactor to form a stream comprising H₂+CO₂. As illustrated in FIG. 2, the total product CO+H₂ stream 305 passes

through a first catalyst filled CO shift reactor 405 and a second catalyst filled CO shift reactor 406 in series with respective outlet streams 306 and 308. The outlet stream 308 passes through heat recovery heat exchanger 420, and the outlet stream 308 passes through heat recovery heat exchanger 414 and, in each of the heat exchangers, heat is used to heat boiler feed-water preheating streams to provide boiler feed-water for waste heat boiler 404.

The stream 308 comprises H_2+CO_2 , but it is understood that any stream described herein as comprising H_2+CO_2 only defines the minimal composition of the stream, and further materials may be present in said stream, such as carbon monoxide and one or more carbon-containing materials. After stream 308 passes through the heat exchanger 414, the stream 308 is cooled in water cooler 416 to near ambient temperature and exits as cooled, crude H_2+CO_2 stream 331. The crude H_2+CO_2 stream 331 preferably can contain substantially all of the CO_2 derived from combustion of carbon in the hydrocarbon feed together with water vapor and minor amounts of CO , CH_4 , N_2 and Ar. Condensed water is separated from cooled, crude H_2+CO_2 stream 331 in separator 407. Water stream 332 from the separator 407 and cooled boiler feed-water stream 334 enter a water treatment unit 411 which produces purified water 55 and an excess water stream 61. The purified water stream 335 (which is recycled for use as the boiler feed-water) is pumped to about 87 bar pressure in pump 415, and boiler feed water stream 316 enters the heat exchanger 414 before passing through heat exchanger 420 to the waste heat boiler 404. The boiler feed-water exiting pump 13 can be at a pressure in the range of about 50 bar to about 120 bar, about 60 bar to about 110 bar, or about 70 bar to about 100 bar.

The saturated steam stream 317 leaving the waste heat boiler 404 first passes through heat exchanger 412 to exit as stream 318, which is compressed in compressor 413. Stream 329 exiting the compressor 413 branches, and steam stream 319 passes through the heat exchanger 412 before combining with methane stream 303 for entry into the GHR 403. Steam in stream 333 passes back through heat exchanger 414 to exit as stream 334 for passage into the water tank/water treatment unit 411.

The steam stream 319 fed to the GHR reactor 403 provides a steam to carbon ratio (carbon combined with hydrogen in the GHR reactor feed) of 6:1 in this case. This high ratio allows 80 bar H_2+CO production pressure with a low quantity of unconverted methane in the total product H_2+CO stream 304. In some embodiments, the steam to carbon ratio can be about 2:1 to about 10:1, about 3:1 to about 9:1, or about 4:1 to about 8:1. Preferably, the steam to carbon ratio is at least 3:1, at least 4:1, or at least 5:1.

The purified H_2+CO_2 product in stream 309 exits the separator 401 and is next processed in a pressure swing adsorber 408 to provide a product stream formed of substantially pure hydrogen in

stream 310 and also provide waste gas comprising CO₂ in stream 311. For example, the substantially pure H₂ product stream 310 can be at a pressure of about 50 bar to about 120 bar, about 60 bar to about 110 bar, or about 65 bar to about 100 bar and can have an impurity level of about 10 ppm to about 200 ppm impurity, about 20 ppm to about 175 ppm impurity, or about 25
5 ppm to about 150 ppm impurity. In some embodiments, the substantially pure H₂ product stream 310 can comprise about 60% to about 98%, about 70% to about 95%, or about 75% to about 92% of the hydrogen from stream 309.

The waste gas in stream 311 preferably contains all the CO₂ plus CO, H₂, CH₄, Argon, N₂ and traces of water vapor previously in stream 309. The waste gas stream 311 is then processed in
10 a low temperature separation unit 409 (e.g., a cryogenic separation unit) as otherwise described herein to form a liquid CO₂ product stream. As discussed above, this is preferably carried out such that at least 50 mol% of the CO₂ in the waste gas stream 311 is separated into the liquid CO₂ product stream. Separated CO₂ is removed in CO₂ stream 312. The remaining vapor phase materials exit the low temperature separation unit 409 in vapor phase stream 313.

The vapor phase stream 313 from the low temperature separation unit 409 can be recycled
15 for a variety of uses. In FIG. 2, the vapor phase stream 313 branches, and a first portion of the vapor phase passes in vapor phase portion one stream 314 through the heat exchanger 412 to combine with the hydrocarbon feed stream 303. In this manner, the remaining impurities are recycled back through the system, particularly being fed back into the GHR reactor 403.

In one or more embodiments, the hydrogen production system can include a combined heat
20 source that is separate from the H₂ + CO synthesis gas generation reactor but that is configured to provide heat that can be provided to one or more streams of the hydrogen production system to increase efficiency thereof. Power production systems can be particularly beneficial for providing a combined heat source. In particular, one or more exhaust streams formed in a power production
25 system can be a combined heat source in that heat can be taken therefrom for transfer to one or more streams in the hydrogen production system.

A particularly beneficial integration of power production and hydrogen production is the gas turbine combined cycle power system. These units are used worldwide usually with natural gas as the fuel. The industrial gas turbine exhaust which is generally at a temperature in the range
30 550°C to 650°C is passed through a large finned tube economizer heat exchanger where it is used to generate high pressure intermediate pressure and low pressure steam for additional power generation using steam turbines. The turbine exhaust at high temperature is suited for use as a combined heat source for addition of heat to the hydrogen production system. Said combined heat source can be used, for example, for preheating the feed streams to the H₂ plant syngas reactors.

Such heating can be in the range of about 400 °C to about 1000 °C, about 425 °C to about 800 °C, about 450 °C to about 600 °C, or about 500°C to about 550°C. Additionally, the excess heat available from the H₂ plant is ideal for boiler feed-water preheating over a temperature range up to 400°C, which releases extra steam for power production in the steam turbines. The main benefit lies in the use of the hydrogen as a fuel in the gas turbine.

In systems and methods as described herein, the use of substantially pure oxygen in the hydrogen plant syngas reactors can have the side benefit of providing a large quantity of substantially pure nitrogen as a by-product from the cryogenic air separation plant. The nitrogen can be provided at relatively high pressure directly from the air separation unit as stream 93. At least a portion of this nitrogen can be blended with the hydrogen that can be produced as described herein. The end result is an H₂ + N₂ fuel gas that is suitable for use in a conventional gas turbine combined cycle power generation system. The blended inert nitrogen is generally required to reduce the adiabatic flame temperature in the gas turbine combustor and has the added benefit of increasing the mass flow of gas in the power turbine. It can also be beneficial to preheat the H₂+N₂ fuel gas and add steam generated from the heat present in the excess boiler feed water stream 59 at a temperature level below 400°C.

The H₂ + N₂ fuel gas can be utilized in any gas turbine combined cycle power generation system. Known systems can be modified as necessary to remove, decommission, or otherwise forego the use of elements that would otherwise be required for removal of CO₂. Known gas turbine combined cycle power generation systems that can be utilized according to the present disclosure are described in US Pat. No. 8,726,628, US Pat. No. 8,671,688, US Pat. No. 8,375,723, US Pat. No. 7,950,239, US Pat. No. 7,908,842, US Pat. No. 7,611,676, US Pat. No. 7,574,855, US 7,089,727, US Pat. No. 6,966,171, and US Pat. No. 6,474,069, the disclosures of which are incorporated herein by reference.

The combination of H₂ production with 100% potential CO₂ capture with a gas turbine combined cycle power generation system using at least a portion of the produced H₂ as fuel provided by the present disclosure results in substantially no atmospheric discharge of CO₂ from the combined system. This provides a distinct advantage over the conventional operation of a gas turbine combined cycle system. In particular, the present combination of systems can eliminate the natural gas fuel typically required in a gas turbine and substitute a fuel with no CO₂ production when combusted. As such, in some embodiments, the present disclosure provides a combination of: 1) an oxygen based hydrogen production unit with near 100% CO₂ capture; 2) a conventional gas turbine combined cycle power generation unit using H₂+N₂ fuel gas that provides power

generation with zero CO₂ emission. The combined system as described herein can provide a surprisingly high efficiency, low cost power generation, and approximately 100% CO₂ capture.

The combination of systems can be implemented in a variety of manners. In some embodiments, an existing combined cycle power station can be converted to eliminate all CO₂ emissions and simultaneously increase the power generation capacity. Such conversion can include addition of the further system components described herein for production of power using a CO₂ circulating fluid and production of H₂ + N₂ fuel gas.

As illustrated in FIG. 2, a gas turbine 410 is provided, and hydrocarbon fuel stream 321 is input thereto for combustion to produce power in generator 417. The gas turbine exhaust stream 322 is passed through the heat exchanger 412 to provide heating to hydrocarbon fuel stream 321, stream 401, stream 317, and stream 319. The temperature of the exhaust stream 322 from the gas turbine 410 can be optionally raised by means of duct-burning using, for example, fresh pre-heated natural gas taken from stream 321 and input to stream 322, or using a waste fuel stream, such as a vapor phase portion two stream 336 taken from stream 313 exiting the low temperature CO₂ separation unit and input to stream 322. This is beneficial to accommodate for required heating duty in the process heater 412, and the duct-burning thus can take place in the piping for stream 322. In some embodiments, streams 336 and 314 may be separate streams exiting the low temperature CO₂ separation unit instead of being branches of a single exit stream, as illustrated.

In some embodiments, a hydrogen production facility as described herein can be particularly suited to provide excess low temperature level heat that can be used in a variety of further systems for a variety of further reasons.

The waste gas from the PSA of the hydrogen production system can be compressed to typically about 200 bar to about 400 bar and mixed with the feed hydrocarbon fuel used in a combustor of a power production system. The waste gas contains not only flammable components CH₄+CO+H₂ but also all the CO₂ produced in the H₂ production system. Alternatively the waste gas from the PSA can be compressed to the inlet pressure of the first PSA, the CO₂ can be removed in one of a number of processes described above, and the CO₂ depleted gas stream can be sent to a second PSA to separate more H₂ to add to the total H₂ product stream. Optionally the waste gas can be preheated in an economizer heat exchanger, steam can be added and more H₂ can be produced in an additional catalytic CO shift reactor, the gas can then be cooled in the economizer heat exchanger before being processed to separate more H₂ in the second PSA. The hydrogen production system is thus suited for production of a significant quantity of low grade heat from the cooling H₂+CO stream at a temperature level of typically below 400°C and preferably in the range 240°C to about 290°C.

Many modifications and other embodiments of the presently disclosed subject matter will come to mind to one skilled in the art to which this subject matter pertains having the benefit of the teachings presented in the foregoing descriptions and the associated drawings. Therefore, it is to be understood that the present disclosure is not to be limited to the specific embodiments described
5 herein and that modifications and other embodiments are intended to be included within the scope of the appended claims. Although specific terms are employed herein, they are used in a generic and descriptive sense only and not for purposes of limitation.

CLAIMS:

1. A process for separating carbon dioxide (CO₂) from a process stream comprising CO₂ and one or more further components, the process comprising:

5 providing the process stream at a pressure such that a partial pressure of the CO₂ in the process stream is at least 15 bar;

drying the process stream sufficiently so that a dew point of the process stream comprising the CO₂ is reduced to a temperature of about -20°C or less;

10 cooling the process stream in at least one heat exchanger to provide the process stream comprising the CO₂ as a two phase stream;

expanding the two phase stream so as to reduce the temperature of the two phase stream to a temperature that is within about 15°C of a freezing point of the two phase stream; and

separating the two phase stream to provide a vapor stream enriched with at least one of the one or more further components and to provide a liquid stream that is enriched with the CO₂.

15 2. The process of claim 1, wherein the drying comprises passage of the process stream comprising the CO₂ through a desiccant-packed bed.

20 3. The process of claim 1, wherein the cooling comprises cooling the process stream against at least a portion of the liquid stream that is enriched with the CO₂.

4. The process of claim 3, wherein the cooling comprises cooling the process stream in a first heat exchanger and in a second heat exchanger.

25 5. The process of claim 4, wherein the cooling comprises cooling the process stream in the first heat exchanger against a first portion of the liquid stream that is enriched with the CO₂ and cooling the process stream in the second heat exchanger against a second portion of the liquid stream that is enriched with the CO₂.

30 6. The process of claim 5, further comprising expanding the first portion of the liquid stream that is enriched with the CO₂ and the second portion of the liquid stream that is enriched with the CO₂ so as to reduce the temperature of the first portion of the liquid stream that is enriched with the CO₂ and the second portion of the liquid stream that is enriched with the CO₂ prior to cooling the process stream in the first heat exchanger against the first portion of the liquid stream

that is enriched with the CO₂ and cooling the process stream in the second heat exchanger against the second portion of the liquid stream that is enriched with the CO₂.

7. The process of claim 6, wherein the first portion of the liquid stream that is enriched
5 with the CO₂ and the second portion of the liquid stream that is enriched with the CO₂ are separately expanded using separate valves.

8. The process of claim 4, further comprising cooling the process stream in a reboiler
10 heat exchanger.

9. The process of claim 8, further comprising passing at least a portion of the liquid
stream that is enriched with the CO₂ through the reboiler heat exchanger.

10. The process of claim 3, wherein the cooling comprises cooling the process stream
15 against at least a portion of the vapor stream enriched with at least one of the one or more further components.

11. The process of claim 1, comprising expanding the two phase stream so as to reduce
20 the temperature of the two phase stream to a temperature that is within about 10°C of the freezing point of the two phase stream.

12. The process of claim 1, wherein separating the two phase stream comprises passing
the two phase stream through a distillation column.

13. The process of claim 12, wherein the distillation column includes a stripping section
25 below a feed point of the two phase stream into the distillation column and includes a rectifying section above the feed point of the two phase stream into the distillation column.

14. The process of claim 1, comprising separating the liquid stream that is enriched with
30 the CO₂ into a first liquid CO₂ stream, a second liquid CO₂ stream, and a third liquid CO₂ stream.

15. The process of claim 14, comprising independently expanding one, two, or three of
the first liquid CO₂ stream, the second liquid CO₂ stream, and the third liquid CO₂ stream so as to reduce a temperature thereof and form a refrigerant stream.

16. The process of claim 14, comprising compressing one, two, or three of the first liquid CO₂ stream, the second liquid CO₂ stream, and the third liquid CO₂ stream.

5 17. The process of claim 1, comprising compressing the vapor stream enriched with at least one of the one or more further components.

18. The process of claim 1, wherein the one or more further components is one or more of a hydrocarbon, carbon monoxide, hydrogen, nitrogen, argon, oxygen, and water vapor.
10

19. The process of claim 1, comprising expanding the vapor stream enriched with at least one of the one or more further components so as to reduce a temperature thereof and form a refrigerant stream.

15 20. The process of claim 1, comprising passing at least a portion of the vapor stream enriched with at least one of the one or more further components through a pressure swing absorber unit.

21. The process of claim 20, wherein said passing is effective to recover at least 60
20 mol% of any H₂ present in the vapor stream enriched with at least one of the one or more further components.

22. The process of claim 1, comprising recycling at least a portion of the vapor stream enriched with at least one of the one or more further components for combination with the process
25 stream prior to said drying step.

23. The process of claim 1, wherein the process stream is an H₂+CO₂ stream from a hydrogen production process.

30 24. The process of claim 1, wherein the process is carried out without using an external refrigerant.

25. A carbon dioxide (CO₂) separation system comprising:

a compressor configured for compressing a process stream, wherein the process stream comprises CO₂ and one or more further components;

a drier configured for removing moisture from the process stream;

at least one heat exchanger configured for cooling the process stream against one or more cooling streams and providing the process stream as a two-phase stream;

at least one expander configured for cooling the two-phase stream via expansion of the two-phase stream; and

a mass transfer column configured to receive the two phase stream and generate a vapor phase stream and a liquid phase stream.

26. A hydrogen production system comprising:

a reactor unit configured for receiving a hydrocarbon feed stream and oxygen and forming a product gas stream comprising H₂+CO;

a steam generating boiler configured for cooling the product gas stream comprising H₂+CO and for forming steam;

at least one reactor configured for receiving the product gas stream comprising H₂+CO and providing a stream comprising H₂+CO₂;

a pressure swing adsorber configured to receive the stream comprising H₂+CO₂ and provide a product stream formed of substantially pure hydrogen and also provide waste gas stream comprising CO₂;

a compressor configured for compressing the waste gas stream comprising the CO₂;

a drier configured for removing moisture from the waste gas stream comprising the CO₂;

at least one heat exchanger configured for cooling the waste gas stream comprising the CO₂ against one or more cooling streams and providing the waste gas stream comprising the CO₂ as a two-phase stream;

at least one expander configured for cooling the two-phase stream via expansion of the two-phase stream; and

a separator configured for separating the two-phase stream into a vapor phase stream and a liquid phase stream.

27. The hydrogen production system of claim 26, further comprising one or more heat exchangers configured for heating the hydrocarbon feed stream against one or both of the product gas stream comprising H₂+CO and the stream comprising H₂+CO₂.

28. The hydrogen production system of claim 26, further comprising one or more heat exchangers configured for transfer of excess heat to an external process.

29. The hydrogen production system of claim 26, further comprising one or more lines configured for output of one or both of a waste fuel gas stream and steam generated in the hydrogen production system.

30. The hydrogen production system of claim 26, further comprising one or more lines configured for delivery of at least part of the product stream formed of substantially pure hydrogen as fuel to a gas turbine.

31. The hydrogen production system of claim 26, wherein the reactor unit comprises a steam plus hydrocarbon plus optionally CO₂ catalytic reformer.

32. The hydrogen production system of claim 26, wherein the reactor unit comprises a partial oxidation unit.

33. The hydrogen production system of claim 26, wherein which the reactor unit comprises a catalytic auto-thermal reformer.

34. The hydrogen production system of claim 26, wherein which the reactor unit comprises a first stage unit that is either an auto-thermal reformer or a partial oxidation reactor and comprises a second stage gas heated steam plus hydrocarbon catalytic reformer.

35. The hydrogen production system of claim 26, wherein at least part of the H₂+CO stream produced from the reactor unit is generated in an ITM partial oxidation reactor using a low pressure preheated feed air stream.

36. The hydrogen production system of claim 26, further comprising a super-heater heat exchanger configured to transfer heat from an external heat source to at least the hydrocarbon feed stream.

37. The hydrogen production system of claim 26, wherein the reactor unit is a combined pressure vessel comprised of a partial oxidation zone and a gas heated reformer.

38. The hydrogen production system of claim 37, wherein the partial oxidation zone is at a bottom portion of the combined pressure vessel, and the gas heated reformer comprises open-ended tubes in a middle zone of the combined pressure vessel and a waste heat boiler heat exchanger at a top portion of the combined pressure vessel.

39. A process for hydrogen production, the process comprising:
reacting a hydrocarbon feed stream and oxygen into a reactor unit to form a product gas stream comprising H_2+CO ;
passing the product gas stream comprising H_2+CO through a steam generating boiler to add steam to the product gas stream comprising H_2+CO ;
converting the product gas stream comprising H_2+CO in at least one reactor to form a stream comprising H_2+CO_2 ;
processing the stream comprising H_2+CO_2 in a pressure swing adsorber to provide a product stream formed of substantially pure hydrogen and also provide waste gas stream comprising CO_2 ;
forming a liquid CO_2 product stream in a cryogenic separation unit operating with auto-refrigeration by passing the waste gas stream comprising CO_2 therethrough such that at least 50 mol% of the CO_2 in the waste gas stream comprising CO_2 is separated into the liquid CO_2 product stream; and
recycling a vapor phase stream from the cryogenic separation unit.

40. The process of claim 39, wherein the cryogenic separation unit operating with auto-refrigeration operates without using an external refrigerant.

41. The process of claim 39, wherein the cryogenic separation unit comprises:
a drier configured for removing moisture from the waste gas stream comprising CO_2 ;
at least one heat exchanger configured for cooling the waste gas stream comprising CO_2 against one or more cooling streams and providing the waste gas stream comprising CO_2 as a two-phase stream; and
at least one expander configured for cooling the two-phase stream via expansion of the two-phase stream.

42. The process of claim 41, wherein the cryogenic separation unit further comprises

a compressor configured for compressing the waste gas stream comprising CO₂, the compressor being positioned upstream from the drier; and

a separator configured for separating the two-phase stream into the vapor phase stream and the liquid CO₂ product stream.

5

43. The process of claim 39, comprising removing CO₂ from the stream comprising H₂+CO₂ prior to processing the stream comprising H₂+CO₂ in the pressure swing adsorber.

10 44. The process of claim 43, wherein removing CO₂ from the stream comprising H₂+CO₂ comprises passing the removing CO₂ from the stream comprising H₂+CO₂ through a chemical or physical solvent based CO₂ removal unit.

45. The process of claim 39, wherein a portion of the waste gas stream comprising CO₂ exiting the pressure swing adsorber is compressed and recycled back to the reactor unit.

15

46. The process of claim 39, wherein at least a portion of the vapor phase stream from the cryogenic separation unit is recycled back to the reactor unit.

20 47. The process of claim 39, wherein the vapor phase stream from the cryogenic separation unit is processed through a second pressure swing absorber to remove at least a portion of any H₂ present in the vapor phase stream prior to recycling of the vapor phase stream from the cryogenic separation unit.

25 48. The process of claim 39, comprising removing at least a portion of any argon and nitrogen present in one or both of the product gas stream comprising H₂+CO and the stream comprising H₂+CO₂ prior to entry of the stream comprising H₂+CO₂ into the pressure swing absorber such that the total concentration of argon and nitrogen in the stream comprising H₂+CO₂ at an inlet of the pressure swing adsorber in the range of about 3 mol% to about 12 mol%.

30 49. The process of claim 39, wherein at least 80 mol% of the CO₂ in the waste gas stream comprising CO₂ is separated into the liquid CO₂ product stream.

50. The process of claim 39, wherein forming the liquid CO₂ product stream in the cryogenic separation unit comprises:

providing the waste gas stream comprising CO₂ at a pressure such that a partial pressure of the CO₂ in the process stream is at least 15 bar;

drying the waste gas stream comprising CO₂ sufficiently so that a dew point of the waste gas stream comprising CO₂ is reduced to a temperature of about -20°C or less;

5 cooling the waste gas stream comprising CO₂ in at least one heat exchanger to provide the waste gas stream comprising CO₂ as a two phase stream;

expanding the two phase stream so as to reduce the temperature of the two phase stream to a temperature that is within about 15°C of a freezing point of the two phase stream; and

10 separating the two phase stream to provide the vapor phase stream and to provide the liquid CO₂ product stream.

51. The process of claim 39, wherein the vapor phase stream from the cryogenic separation unit is passed through a catalytic CO shift unit with an economizer heat exchanger, has steam added thereto, and is then passed through a catalytic reactor to convert at least a portion of
15 the contained CO by reaction with the steam to form a further stream comprising H₂+CO₂ and to form a gas stream containing at least 60 mol% H₂.

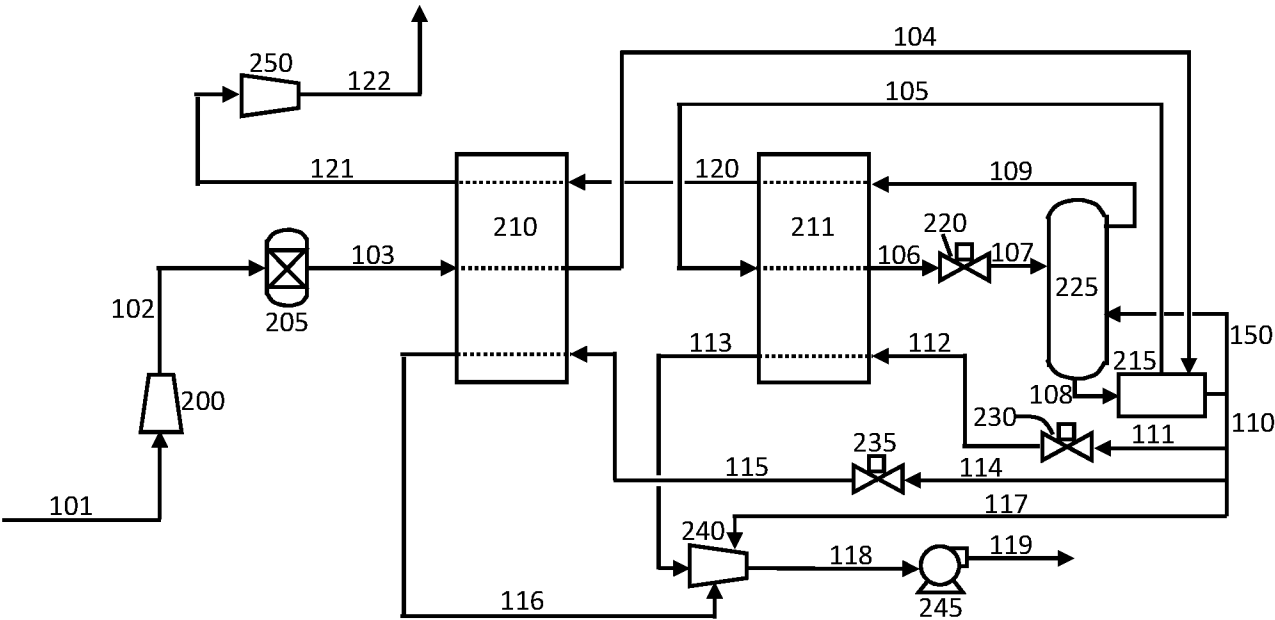


FIG. 1

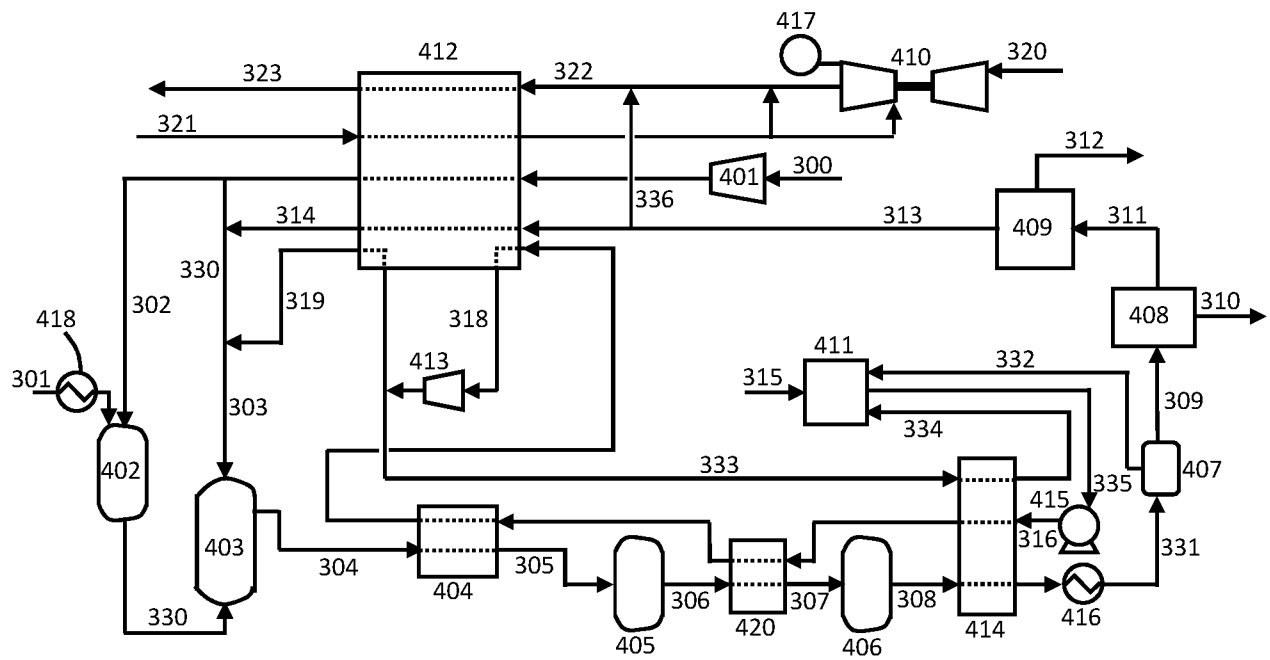


FIG. 2