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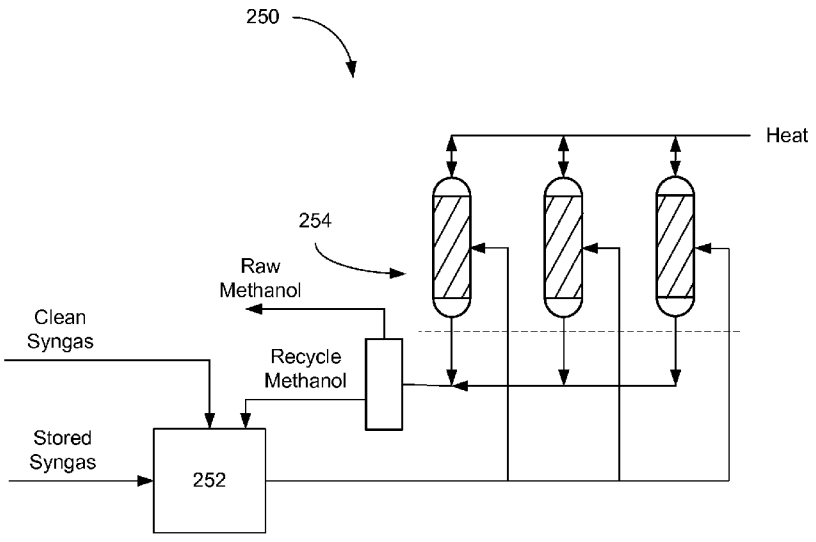
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(54) Title: SYSTEMS AND METHODS FOR CYCLIC OPERATIONS IN A FUEL SYNTHESIS PROCESS



(57) Abstract: A method, apparatus, and system for a fuel synthesis system including a multiple methanol reactor train, operated in parallel from a common input of 1) synthesis gas from a solar driven chemical reactor and 2) synthesis gas from a storage tank. In some embodiments, the multiple methanol reactor trains are idled as needed based on a variable amount of synthesis gas fed into the process. Additionally, some embodiments may include a controller to control operation of the multiple methanol trains by potentially idling one or more of the methanol reactor trains, switching to an operational state, or altering the output from the reactor trains, based on the amount of synthesis gas being generated by the solar driven chemical reactor, which is subject to marked variations in volume of synthesis gas output based on a seasonal, diurnal and weather effects.

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SYSTEMS AND METHODS FOR CYCLIC OPERATIONS IN A FUEL SYNTHESIS PROCESS

RELATED APPLICATIONS

[001] This application claims the benefit of both U.S. Provisional Patent Application Serial No. 61/248,282, filed October 2, 2009 and entitled "VARIOUS METHODS AND APPARATUSES FOR SUN DRIVEN PROCESSES," and U.S. Provisional Patent Application Serial No 61/185,492, entitled "VARIOUS METHODS AND APPARATUSES FOR SOLAR-THERMAL GASIFICATION OF BIOMASS TO PRODUCE SYNTHESIS GAS" filed June 9, 2009.

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FIELD OF THE INVENTION

[003] Embodiments of the invention generally relate to systems, methods, and apparatus for refining biomass and other materials. More particularly, an aspect of an embodiment of the invention relates to solar-driven systems, methods, and apparatus for refining biomass and other materials.

BACKGROUND OF THE INVENTION

[004] Biomass gasification is an endothermic process; energy must be put into the process to drive it forward. Typically, this is performed by partially oxidizing (burning) the biomass itself. Between 30% and 40% of the biomass must be consumed to drive the process, and at the temperatures which the process is generally

limited to (for efficiency reasons), conversion is typically limited, giving still lower yields. In contrast, the proposed solar-driven biorefinery uses an external source of energy (solar) to provide the energy required for reaction, so none of the biomass needs to be consumed to achieve the conversion. This can result in significantly higher yields of gallons of gasoline per biomass ton than previous technologies, as the energy source being used to drive the conversion is renewable and carbon free. In addition, chemical reactors are generally engineered to operate at constant conditions around the clock.

SUMMARY OF THE INVENTION

[005] Some embodiments relate to a solar-driven chemical plant, including a solar thermal receiver having a cavity with an inner wall, where the solar thermal receiver can be aligned to absorb concentrated solar energy from one or more of 1) an array of heliostats, 2) solar concentrating dishes, and 3) any combination of the two.

[006] In some embodiments, a fuel synthesis system including a multiple methanol reactor train, operated in parallel from a common input of 1) synthesis gas from a solar driven chemical reactor and 2) synthesis gas from a storage tank. Some embodiments may include a controller to control operation of the multiple methanol trains by potentially idling one or more of the methanol reactor trains or reducing output of the trains based on a lower amount of synthesis gas being generated by the solar driven chemical reactor, or switching an idle train to an operational state or increasing output of a train when the amount of syngas gas is higher, both of which are subject to marked variations in volume of synthesis gas output based on a seasonal, diurnal and weather effects. Additionally, in some embodiments the multiple methanol reactor trains are idled as

needed based on a variable amount of synthesis gas fed into the process.

[007] In some embodiments, a fuel synthesis system can include control algorithms on reactor operation. The control algorithms may specifically allow rapid and efficient reactor cycling. This can be by using synthesis gas from a solar driven chemical reactor. Additionally, synthesis gas from a storage tank may provide for rapid and efficient reactor cycling, e.g., by maintaining reactor temperature. Recycling synthesis gas and methanol product gas from the outlet of the reactor trains can also be used to keep at least one of the trains operating at some percent of its maximum throughput.

BRIEF DESCRIPTION OF THE DRAWINGS

[008] The drawings refer to embodiments of the invention in which:

figure 1 illustrates a block diagram of an embodiment of an example process flow in accordance with the systems and methods described herein;

figure 2A illustrates a diagram of an embodiment of a solar chemical reactor in accordance with the systems and methods described herein;

figure 2B illustrates a diagram of an embodiment of methanol reactor train;

figure 3 illustrates a diagram of an embodiment of a quenching via an injection cooling medium into reaction products, gas clean up, and ash removal system;

figure 4 illustrates a diagram of an embodiment of an example quenching, gas clean up, and ash removal system; and

figure 5 illustrates a diagram of an embodiment of a multiple level compressor system strategy.

[009] While the invention is subject to various modifications and alternative forms, specific embodiments thereof have been shown by

way of example in the drawings and will herein be described in detail. The invention should be understood to not be limited to the particular forms disclosed, but on the contrary, the intention is to cover all modifications, equivalents, and alternatives falling within the spirit and scope of the invention.

DETAILED DISCUSSION

[0010] In the following description, numerous specific details are set forth, such as examples of specific data signals, named components, connections, number of reactor tubes, etc., in order to provide a thorough understanding of the present invention. It will be apparent, however, to one of ordinary skill in the art that the present invention may be practiced without these specific details. In other instances, well known components or methods have not been described in detail but rather in a block diagram in order to avoid unnecessarily obscuring the present invention. Further, specific numeric references such as first reactor tube, may be made. However, the specific numeric reference should not be interpreted as a literal sequential order but rather interpreted that the first reactor tube is different from a second reactor tube. Thus, the specific details set forth are merely exemplary. The specific details may be varied from and still be contemplated to be within the spirit and scope of the present invention. The term coupled is defined as meaning connected either directly to the component or indirectly to the component through another component.

[0011] Some embodiments relate to a solar-driven fuel synthesis system configured for cyclic operations in a fuel synthesis process. In some embodiments, a fuel synthesis system including a multiple methanol reactor train, operated in parallel from a common input of 1) synthesis gas from a solar driven chemical reactor and 2) synthesis gas from a storage tank. Some embodiments may include

a controller to control operation of the multiple methanol trains by potentially idling one or more of the methanol reactor trains based on theamount of synthesis gas being generated by the solar driven chemical reactor, which is subject to marked variations in volume of synthesis gas output based on a seasonal, diurnal and weather effects. Additionally, in some embodiments the multiple methanol reactor trains are idled as needed based on a variable amount of synthesis gas fed into the process.

[0012] In some embodiments, a fuel synthesis system can include control algorithms on reactor operation. The control algorithms may specifically allow rapid and efficient reactor cycling. This can be by using synthesis gas from a solar driven chemical reactor. Additionally, synthesis gas from a storage tank may provide for rapid and efficient reactor cycling, e.g., by maintaining reactor temperature. Recycling synthesis gas and methanol product gas from the outlet of the reactor trains can also be used to keep at least one of the trains operating at some percent of its maximum throughput.

[0013] Although some embodiments apply to a wide variety of chemical reactors, for brevity and clarity this discussion focuses on the synthesis of methanol from synthesis gas. It will be understood by those of skill in the art that the systems and methods described herein might be applied to other chemical reactors.

[0014] Figure 1 illustrates a block diagram of an example process flow. Some embodiments encompass a solar-driven-biomass gasification to liquid fuel/electrical process. The process might also include generation, chemical processing, or bio-char, for solar generated synthesis gas derivative product or other similar technical process. In a specific example implementation the process described is a solar-driven-biomass gasification to 'green' liquid fuel

process. In an embodiment, this process includes one or more of the following process steps.

[0015] The integrated chemical plant includes several process steps including a grinding system 100 for making biomass particles and other chemical feed preparation process that is run on an as-needed basis, a chemical reactant feed system 104 that supplies chemical reactant, including the biomass particles, when the solar driven chemical reactor is at at least its minimum operating temperature, a solar concentrating field process 110 that is stowed when not in use and aligned to focus the concentrated solar energy at the solar driven chemical reactor 106 at least near sunrise. This near sunrise could be roughly within 90 minutes of Sunrise depending on time of year and current weather conditions. The solar driven chemical reactor process 106 is kept at or near operating temperature during off production hours, a compressor process 114 that switches levels of compression between compressing and idling twenty four hours a day, a synthesis gas clean-up process 108, an intermediate chemical generation process 116 such as methanol synthesis, and a final stage chemical process 124 such as generation of a liquid hydrocarbon fuel process such as methanol to gasoline.

[0016] Some process steps may be started in parallel with other process steps, while others may run continuously and just change states from idle to operational.

[0017] Biomass grinding or densification, transport and offload 100 may be part of the overall process. Bales of the biomass can be compressed and densified by a compactor to facilitate transport to on-site via the densification achieved by the double compression.

[0018] A grinding system 100 couples through storage 102 to the entrained-flow biomass feed system 104. A conveyer brings the biomass to the grinding system that grinds biomass into particles via a mechanical cutting device cooperating with a set of filters with specific sized holes in the filters. The grinding system generates

particles that have an average smallest dimension size between 200 microns (um) and 2000 um in diameter, such to fit through the holes in the filters, with a general range of between 500 um and 1000 um, and then the particles are loaded into a feed vessel such as a lock hopper system with a standard belt or pneumatic conveyer. The biomass may be in an embodiment non-food stock biomass. In other cases, food stock biomass or a combination of the two might also be processed.

[0019] Two or more feed line supply the particles of biomass having an average smallest dimension size between 50 microns (um) and 2000 um to the chemical reactor. An entrained gas biomass feed system uses an entrainment carrier gas to move a variety of biomass sources fed as particles into the solar driven chemical reactor.

[0020] A solar receiver and gasifier 106 may be used to break down the biomass. An example biomass gasifier design and operation can include a solar chemical reactor and solar receiver to generate components of synthesis gas. The feed-forward portion and the feedback portion of the control system adapts the operation of the reactor to both long and short term disturbances in available solar energy. Various solar concentrator field designs to drive the biomass gasifier can be used. Some example systems may include a solar concentrator, focused mirror array, etc. to drive biomass gasifier 110.

[0021] Quenching, gas clean up, and ash removal from biomass gasifier 108 occur to make the produced synthesis gas useable for the next process step. Some gasses generated in the chemical reactor may be a waste product, while other gasses can be compressed 114 prior to storage 118 or sent directly for methanol synthesis 116. Methanol may then be stored 120 for later methanol to gasoline conversion 122.

[0022] A storage capacity of the synthesis gas and idling of the methanol trains is created to decouple a response rate of the methanol synthesis plant from the response rate of the solar driven chemical reactor. The storage capacity and idling processes established for the integrated solar driven chemical plant also decouples a direct production rate of the synthesis gas generated in the solar driven chemical reactor from the supply requirements of the methanol synthesis plant.

[0023] An on-site fuel synthesis reactor that is geographically located on the same site as the chemical reactor and integrated to receive the hydrogen and carbon monoxide products from the gasification reaction can be used in some embodiments. Additionally, the on-site fuel synthesis reactor has an input to receive the hydrogen and carbon monoxide products and use them in a hydrocarbon fuel synthesis process to create a liquid hydrocarbon fuel. The on-site fuel synthesis reactor may be connected to the rest of the plant facility by a pipeline that is generally less than 15 miles in distance. The on-site fuel synthesis reactor may supply various feedback parameters and other request to the control system. For example, the on-site fuel synthesis reactor can request the control system to alter the H2 to CO ratio of the synthesis gas coming out of the quenching and gas clean up portion of the plant and the control system will do so.

[0024] In various embodiments, synthesis gas may be fed to another technical application.

[0025] For example, some embodiments may use a series of compressors to provide compression 114. Such a system might include at least three levels of compression. In some embodiments, a first low-pressure stage, of less than 500 PSIG may be located in a synthesis gas clean up portion of a system just prior to an amine step. Other embodiments may include a low-pressure level that is less than 500, 250, or 100 PSIG, for example, depending on the

specific embodiment. An intermediate pressure 500-1500 PSIG level for injecting cleaned up solar generated synthesis gas into a common input into the methanol process may be located and a third stage level for pumping excess synthesis gas from the solar chemical reactor into a high pressure 2000-3000 PSIG storage tank.

[0026] In some embodiments, the synthesis gas exits the storage vessels 118 or the synthesis gas compressor 114 to enter the methanol synthesis unit 116. The unit 116 may comprise standard shell and tube Lurgi style methanol reactors. This is a well-known process and is operated on very large scales (millions of gallons of methanol per year) worldwide. The process operates at a 4:1 recycle ratio and converts 96% of the synthesis gas to methanol. In an embodiment, the process operates at another example 7.5:1 recycle ratio and conversion of 95% of the synthesis gas to methanol. The raw methanol is distilled from the entrained water product and fed to a standard methanol-to-gasoline (MTG) unit, where the methanol is converted to gasoline and LPG.

[0027] In various embodiments, synthesis gas may be feed to another technical application. Examples include a synthesis gas to other chemical conversion process. The other chemical of chemicals produced can include liquefied fuels such as transportation-liquefied fuels. Some transportation-liquefied fuels include jet fuel, DME, gasoline, diesel, and mixed alcohol, bio-char with a high sequestered amount of carbon; chemical production, electricity generation, synthetic natural gas production, heating oil generation, and other similar synthesis gas based technical applications. In an example hydrocarbon based fuel, e.g., methanol, 116 may be formed from synthesis gas. The methanol may be further converted to gasoline or other fuels 122 and various products may be separated out from the gasoline 124 or synthesis gas. These products, e.g., gasoline, may then be stored for later use as an energy source.

[0028] In starting large motor(s) such as those involved with the compression of gases in a synthesis plant, large electrical demands are placed on the electrical power grid. Such demand is not only costly but can also exceed the infrastructure capacity to deliver the needed power. If these large motors for, say, compressors, are idled frequently, say in a diurnal fashion, such costs or limitations may prevent the diurnal cycling. Accordingly, some embodiments may couple the stored angular momentum of a flywheel to the motor to provide the majority of motive force required for motor starting.

[0029] A flywheel drive mechanism may be used to start the compressors. The flywheel drive mechanism may including a flywheel sized such that it can store enough rotational energy to start a compressor and small enough to be started using less power than is needed to start the compressor. A low power starting mechanism may be used to starting the flywheel. The low power starting mechanism can provide enough power to rotate the flywheel, but less power than is needed to start the compressor. Using a flywheel to start the compressor can decrease or eliminate surges in electrical power that might otherwise be needed to start a compressor because the speed of the flywheel builds over time as power is received from the low power starting mechanism. Additionally, a mechanism to couple the fly wheel to the compressor is used so that rotational energy from the fly wheel can be transferred to the compressor to start the compressor. Although discussed in the context of electrical load, a flywheel might be applied to assisting with other motive force replacement, like a steam drive etc.

[0030] Accordingly, some embodiments might start large motors without high electrical demand, start large motors without high stress on motor windings etc., and allow cycling of motors in situations where recirculation of compressor feed/effluent is not a viable

solution. Such a system may provide for lower power charges and longer motor life in the face of many starts and stops.

[0031] In some embodiments, motors are coupled to the rotational energy of a flywheel. Coupling can be in various ways, e.g., mechanically direct through a clutch, via hydraulics where the flywheel supplies the power to the hydraulic pump, etc. When the motor is started the power brought to bear on the motor shaft can be from the storage energy of a flywheel. Additionally, the motor can be started in a variety of modes. For example, a hybrid mode where both electricity and flywheel energy is simultaneously applied, a sequential mode, e.g., flywheel energy is applied and then transitioned to electrical energy, etc.

[0032] Additionally, in some embodiments, flywheel energy can be accumulated in various ways. For example, slowly over time from a smaller motor that does not place large demands on the infrastructure, or flywheel energy can be added from the motor itself as operates and/or as it shuts down during the idle process.

[0033] Figure 2A illustrates a diagram of an embodiment of a solar gasifier (reactors) 200 in accordance with the systems and methods described herein. As illustrated in Figure 2, the reactor 200 can take in biomass particles in a carrier gas stream 210 and output synthesis gas 212.

[0034] The reactor 200 can receive solar energy 202 through a window or aperture. This solar energy 202 may be used to heat a solar heated reactor chamber 206 that can be located within a receiver cavity. This reactor chamber can included reactor tubes that contain biomass particles as the particles follow through the reactor. The biomass particles may be heated to a temperature such that they react inside the tubes. After biomass particles react within the tubes

of the reactor chamber 206 the reaction products can be quenched 208 to prevent back reaction.

[0035] In some embodiments, a fuel synthesis system can include a multiple methanol reactor train 214. The multiple methanol reactor train 214 may be operated in parallel from a common input of 1) synthesis gas from the solar driven chemical reactor 200 and 2) synthesis gas from a storage tank. The synthesis gas from the storage tank can allow the methanol reactor train 214 to continue operation when the supply of synthesis gas from the solar driven chemical reactor 200 is low. Additionally, the storage tanks may include at least one of a tank, a pipeline, or an underground structure. Underground geologic formations can include salt domes, injection wells, etc.

[0036] In some embodiments, multiple methanol reactor trains 214 are physically separate reactor trains. The physically separate reactor trains can be in parallel with each other. In other embodiments, the multiple methanol reactor trains 214 include a common reactor with a manifold that feeds multiple virtual reactor trains from that manifold. For example, the multiple methanol reactor trains 214 may be incased in the shell of the common reactor. In some embodiments, the methanol reactors can be a shell and tube reactor.

[0037] When the reactor train 214 is temporarily idled it may be kept at or near the reaction temperature with heat makeup as required to offset heat losses. This heat may be provided by one or more of 1) heat from boiling water heated from an external boiler, 2) heat from the methanol synthesis reaction from another methanol reactor that is operating, 3) an internal electric heater, 4) other sources, or any combination of the four.

[0038] In some embodiments, the reactor 214 can be a shell and tube reactor. In such a system, the shells of each reactor train may be interconnected. By interconnecting the shells, a hot working fluid can be used to remove the exothermic heat from a train that is operating and to circulate the fluid around idle trains to keep the idle trains near reaction temperature and the reactor uses layers of insulation around the methanol reactor train to keep the plant near reaction temperature. Also, each of the reactor trains may share a common shell that may be heated similar to above.

[0039] A temporarily idled reactor might also be kept at or near the reaction temperature with waste heat from other areas of the plant. For example, waste heat from the quenching operation on the synthesis gas coming out of the solar driven chemical reactor might be used. The waste heat may be stored in a solid whether a monolithic block including rock or carbon or a composite like concrete; pieces of solid including gravel; molten solids including a salt or blend of salts; heated liquids; or heated pressurized vapor, such as steam; or combinations of the above. This waste heat is provided during the operation of the solar driven reactor. When the weather events are not blocking the sun, the sun may provide massive amounts of excess heat, which exist in the synthesis gas gas products coming out of that chemical reactor and need to be rapidly quenched, generally within 0.1 to 10 seconds. This waste heat can be captured during the quench and may be stored in a variety of ways including those listed above in this paragraph and used later as a heat source when the weather conditions cause the synthesis gas supply to go low. When the synthesis gas supply is low, the heat from the thermal storage may be used to heat the idle methanol reactors.

[0040] In some embodiments, before a reactor train 214 goes idled, the H2 content inside the methanol reactor may be boosted by

adding synthesis gas with a higher ratio of H2:CO from the solar driven reactor or adding supplemental H2 from an H2 storage supply. The H2 concentration in the idled reactor(s) may be adjusted at this point, if required, to ensure that a reducing atmosphere is maintained within the reactor. This atmosphere allows the cyclic operation of the methanol synthesis plant with little to no additional loss in heterogeneous catalytic activity or throughput over the plant's lifetime other than through aging and the catalytic activity itself.

[0041] A multiple methanol reactor 214 system can include, for example, at least two methanol reactors that are operable at a percentage of maximum throughput such that the fuel synthesis system has a dynamic range of at least 16 to 100 percent. This gives the plant at least a 5:1 dynamic range when the reactors are equally sized and each capable of 50% individual turn down. In additional embodiments, the multiple methanol reactor 214 system can include at least two methanol reactors that are operable at a percentage of maximum throughput such that the fuel synthesis system has a desired dynamic range. The methanol reactors may be equally sized reactors each of equal 50% turn down or the individual reactors may have different capacities and varying turn down percentage from for example 100 to 1, and 100 to 20. In short, most process will not run with 100% turn down. Typically there is no motivation to pay the extra to have high turndown as process is designed to run at steady state near capacity. This integrated plant's design however, requires frequent change in output. This increased dynamic operating range costs significant money and thus is not an obvious alternative for a non-cycling process. Increased dynamic operating range can require, for example, extra compressors (of small size) etc. to operate in parallel with a normal compressor suite. Many processes with non-desired parallel reactions may have to operate at a given gas velocity so that there is not time for the undesired reaction to occur.

To turn such a reactor down near 100% enhances side reaction activity and lowers or ruins the quality of product.

[0042] Figure 2B illustrates a diagram of an embodiment of a methanol reactor train 250. The methanol reactor train 250 is for the cyclic operation of the fuel synthesis section downstream of solar synthesis gas production. Chemical reactors and their processes are traditionally engineered to operate at constant conditions 24 hours per day, 7 days per week. In applications such as the solar generation of synthesis gas, however, marked variations in synthesis gas output on a seasonal, diurnal and weather modulated basis can occur. Processes, such as the example application, that are downstream of the solar generation of synthesis gas can be engineered to operate in this highly variable environment.

[0043] For example, a downstream fuel synthesis process can have its parameters controlled to account for the cyclic supply of solar generated synthesis gas as a feed product. Thus, the parameters such as temperature, pressure, and chemistry of the fuel synthesis plant can be controlled during idle non-production periods of time so that the fuel synthesis plant may rapidly resume to fuel product when the supply of solar generated synthesis gas resumes in sufficient quantities.

[0044] In some examples, cyclic operation of chemical reactors 254 may be subject to highly variable feedstock flows. Additionally, a solar driven plant may generally provide cyclic operation of the fuel synthesis process due to the cyclic nature of the availability of sunshine.. The synthesis gas flow to the synthesis process may be discontinued at the end of each solar day or from time to time during the day or night. The H2 concentration in the idled reactor(s) can be adjusted at this point, if required, e.g., to ensure that a reducing atmosphere is maintained within the reactor(s). This atmosphere can

allow the cyclic operation of the methanol synthesis plant with little to no loss in heterogeneous catalytic activity or throughput over the plant's lifetime, for example, when a conventional catalyst is used in fuel synthesis.

[0045] The temporarily idled reactor(s) can be kept at or near the reaction temperature with heat makeup as required to offset heat losses. An example embodiment of this is the use of boiling water in, for example, shell and tube reactors that can be heated from an external boiler. Additionally, the temporarily idled reactor(s) can be kept at or near the reaction pressure, such as within 70% of operating reaction pressure or greater. Temperature and pressure conditions may be specified not only to allow the rapid restart of the reactor trains but also to assure that products or phases that can damage equipment, product quality, catalysts, etc. do not form. One example system can use a boiling water shell reactor or mini-reactor with high heat removal capability to keep synthesis system warm. The reactors can be isothermal boiling water shell and tube reactors with the catalyst packed in the tubes. Additionally, the fuel synthesis reactor shell can be well insulated. This configuration can allow a fuel synthesis reactor to be maintained at a warm idle and restarted with little consequence. Additionally, pumps and compressors may be kept in re-circulation mode or may also be idled and the fuel synthesis reactor restart occurs when synthesis gas is again made available to the reactor.

[0046] In some applications, such as the solar generation of synthesis gas, marked variations in feedstock availability, on at least a diurnal basis, occur. Such variability may normally be handled through feedstock storage so that a steady rate of feedstock can be supplied to the chemical reactor. In some cases, the cost or other problems of storage can leave no alternative but to operate the chemical reactor on a cyclic basis.

[0047] Commercial methanol reactors are designed with the goal of steady state operation 24 hours a day, 7 days a week. Unlike commercial methanol reactors, some embodiments described herein may be designed for cyclic operation. For example, some embodiments may be designed for diurnal operation to allow for the production of liquid fuels in solar feedstock production environments. Some systems may operate chemical reactors in a non-batch cyclical environment. Additionally, the example systems may idle and restart reactors routinely and in a timely fashion and avoid the costs of extensive feedstock storage.

[0048] Reactor construction may be tailored to specifically allow rapid and efficient reactor cycling. Reactors and perhaps process piping and equipment can be insulated and supplied with a means of maintaining temperature and pressure. For example, a small boiler or resistance heaters can provide in the boiling water shell of tubular reactor(s) to maintain temperature. Insulation is not required but can lower the energy costs of maintaining process temperature during times when the reactor is not actively processing.

[0049] Reactor operation and control algorithms may specifically allow rapid and efficient reactor cycling. Additionally, reactor and pump control algorithms can allow very broad dynamic range of operations. When feedstock availability decreases beyond the dynamic range of the reactor(s), each reactor can be warm idled by shutting off feedstock flow and, if desired, recycle flow. Accordingly, the reactor can be maintained at or near reaction temperature and pressure and if required, hydrogen can be injected to assure the gas environment remains reducing.

[0050] When feedstock is available, it can be mixed with the recycle stream, if any, and feed into the reactor that is already hot and at pressure. Additionally, the feed stream can be preheated. In

some embodiments, when using a boiling water shell and tube reactor, there can be enough thermal mass in the reactor to heat to keep the reaction zones hot enough for reaction to begin. In the methanol case, which is exothermic, heat can be available as a reaction by-product.

[0051] Some embodiments can provide a wide dynamic range for chemical reactor use in solar bio-refineries. Chemical reactors being fed by feedstocks of cyclic availability (e.g., diurnal with cloud events) can require a wide dynamic range to continue production under a wide variety of feedstock flow rate conditions. Three ways to handle a variable amount of solar generated synthesis gas being supplied as an input might be used. These ways include (1) use of a number of parallel fuel synthesis reactors, (2) use of storage tanks to store and supplement the supply of solar generated synthesis gas, and (3) a hybrid of both parallel trains and a limited amount of storage mechanisms of supplemental synthesis gas.

[0052] Normally designed reactors are designed to generally run 24-7 at a single point and often have dynamic ranges allowing operation from 100% to 50%. In an example solar reactor situation a dynamic range from 100% - 17% could be needed. To achieve this, a suite of parallel reactors 254 may be treated, from an overall control perspective, as a single reactor. Integrated local reactor controllers vary each reactors performance to achieve the required overall product quality and output. For example, three equal sized reactors, each with a design turndown of 50%, can achieve a turndown (as a set) of below 17%. Of course, depending on the size of the individual reactors and their individual turndown ability, the number of reactors needed to meet a specific wide dynamic range requirement will vary anywhere from one reactor to many.

[0053] In some embodiments, each reactor in the train may be of the same capacity or of different size capacities. The turn down range of the overall set may be from 100 - 1% depending on the number of parallel reactors used. Accordingly, systems may turn the operation of the parallel reactors up, down, on, and off to track and balance the variable amount of synthesis gas being supplied, controlling the variability seen by each reactor to be within its dynamic range, to keep the system operating during the cyclic ups and down of the supplied synthesis gas. Further, portions of the reactor suite may be shut down completely during certain times if required.

[0054] These wide dynamic range suites may include of multiple reactors, reactor(s) with multiple internal feed structures that can be modulated, or both. Thus, multiple trains to start up and shutdown to respond to the potentially dynamic nature of the amount of synthesis gas feed or a single train with multiple internal manifolds feeding different capacity zones within the single reactor may be used.

[0055] Re-circulated end-product gas and/or tail gas fed back to the supply input flow strategies may also be applied to assure a smooth controlled response to variability. When operating during a time of rapid decrease in solar generated syngas, a portion of the output product gas (methanol) and other tail gases (CO2 and methane) these products may be recycled back into the synthesis gas feed into the parallel reactor trains. This control technique allows for the hardware of the fuel synthesis reactor plant to more gradually change up and down than the supplied solar generated synthesis gas. The supplemental re-circulated output product gas (e.g. methanol) and other tail gases (e.g. CO2 and Methane) increases or decreases to make up for the swing in the supplied solar generated synthesis gas and thereby contributes to the more stable operation of the fuel synthesis plant.

[0056] Accordingly, some embodiments may use established fuel synthesis techniques adapted for a variable amount of synthesis gas fed into the process. High-pressure synthesis gas storage and parallel trains of methanol reactors that maintain near or close to full reaction temperature and pressure 24-7 even when no synthesis gas is flowing to one or more of the parallel trains may be used. A control system operating the suite of parallel reactors 254 may be designed to tolerate transient flow of synthesis gas operation. The control system of the process for transient synthesis gas feed can dictate the extent of such synthesis gas storage capacity and when it will be saved or used, how many trains will be in operation, amount of recirculation of output gases back into the input feed, rate at which each train is operating at, and other similar plant parameters.

[0057] The control system and hardware designs can provide the ability to perform routine cycling, due to the diurnal solar energy source, of the rates of production in the methanol synthesis plant. The synthesis gas can be stored directly in gaseous form or in other phases via changes in temperature, pressure, chemical reaction, absorption, etc. The solar generated synthesis gas from the chemical reactor is compressed and fed either into a storage system or directly into the methanol synthesis unit, depending on the process needs at the time of production.

[0058] Solar produced, renewable, synthesis gas may be stored for multiple uses within the solar biorefinery. For example, stored synthesis gas may be combined 252 with clean synthesis gas from a solar reactor for conversion to methanol. Use may occur during start-up, during cloud events, during the night, during times of over production or at other times. A few examples include using the stored gas to feed or stabilize feed flow rates to compressors during start-up or short-term cloud events and using the stored gas to capacity buffer the amine unit or other unit operations during cloud

events. The stored synthesis gas may also feed the methanol synthesis reactor trains during start-up, cloud events, and during the night. Synthesis gas may be stored as a compressed gas or absorbed into a solid, or in a liquid form.

[0059] The methanol synthesis reactors 254 can be standard boiling water shell packed tube (Lurgi style) reactors, using a Cu/ZnO/Al203 catalyst. The exothermic heat of reaction can be removed by boiling water on the shell side of the reactor. The product methanol then passes through a heat exchanger to preheat the feed stream and two additional heat exchangers in order to bring the temperature to an appropriate level for separations (66 °C). The product stream then enters a flash drum, where the un-reacted synthesis gas can be separated from the raw methanol and water products. Some of the un-reacted synthesis gas is purged (as it contains some inert CO2 not removed by the amine system, which would build up in the system) and it can be recompressed by a bank of three recycle compressors (again, for turndown reasons), after which it rejoins the feed stream from the solar process or the synthesis gas storage area.

[0060] If this design has enough storage to store an entire year's production of synthesis gas, a synthesis plant could be operated similarly to current methanol synthesis operations. Due to the high cost of compressed gas storage, this is generally not an option for the design of some of the embodiments of this solar thermal biorefinery. Similarly, if the methanol plant was of inconsequent cost and had the same dynamic range as the gasifier, the entire plant could be built to the maximum throughput (as determined by solar energy availability) and no storage would be needed at all. Yet this is generally not the case for either.

[0061] As a result, the configuration used in some embodiments is a balance between the cost of excess methanol synthesis capacity and the cost of gas storage. In one example, a storage implementation may maintain production at summer operational capacity for approximately 12 hours. The plant could then run 24-7 during the summer months. In the winter, the storage could be filled over several days time and then the synthesis operation taken out of idle to run for an uninterrupted length of time before returning to idle and extended storage filling.

[0062] The synthesis gas produced by the solar process is principally comprised of hydrogen, carbon monoxide, and some (~5%) carbon dioxide and water. To avoid corrosion problems in a metal storage container, this gas should be dry or the storage container should be coated or protected . Many options exist for synthesis gas storage. For example, a pipeline can be used as a very effective storage container for synthesis gas.

[0063] There are three areas of general concern when storing synthesis gas in a pipeline or vessel: hydrogen embrittlement, CO stress corrosion cracking and formation of iron carbonyl, the presence of moisture, which with the carbon dioxide present in the gas can form an acidic environment. At the specified process conditions and using carbon steel pipe, hydrogen embrittlement is not a pipeline failure risk. CO effects can be mitigated via a plastic liner, which is formed in-situ in the pipeline as it is laid. Even without the liner CO stress cracking effects can also be mitigated by drying of the gas stream. In addition, our synthesis gas storage temperature is low, (about 32 °C with a short term maximum of about 55 °C, well below the 200 °C temperature for maximum carbonyl formation. Even without a liner, carbonyl formation rates are low enough that pipeline lifetime may not be compromised. Catalyst risk can be

mitigated by a polishing bed. The pipeline may generally need to be protected from carbonic acids.

[0064] For example, in a particular embodiment a pipeline might be used for storage. At the pressures and temperatures generally used in some embodiments, dry synthesis gas can be stored in carbon steel pipes, using, for example, technology developed for natural gas pipelines. In one example, the pipeline is 24 inches in diameter and about 16 miles long and is buried around the perimeter of the solar field. The synthesis gas is pressurized to a maximum Psig, for example, of 3000 PSIG. In the absence of water, the carbon dioxide component can be stored safely in these vessels. Liquid carbonyls that may form during storage may be eliminated with appropriate liquid traps before the gas is sent to the synthesis side of the plant.

[0065] The pipeline may also be made from plastics, composites, or laminates. Additionally, the pipeline may be below ground or above ground or both. The pipeline can be used as the storage mechanism. Additionally, absorbents such as a hydride for H2 and another absorbent for CO may be place in the storage mechanism/pipeline may provide the same or an even greater amount of storage capacity of the synthesis gas while being stored at a lower pressure.

[0066] In some embodiments, the synthesis gas can be stored at 3000 psig and can be delivered to the methanol synthesis process at 1200 psig. The actual maximum storage pressure will be an economic optimization that accounts for the reactor pressure, compression costs, storage costs, operational demands, etc. Synthesis gas can leave the storage tanks through an expander and heat exchanger, or the direct synthesis gas compressor as described below and may be mixed with recycled synthesis gas from the

methanol process. The synthesis reactor can operate with no recycle as a single pass reactor or can operate with a variety of recycle ratios with a preferred range being 3:1 – 5:1 Additionally, the blended stream can be preheated with the waste heat from the methanol reactor product stream and is fed to a bank of one or more methanol synthesis reactors in parallel. The parallel ganging of methanol reactors may allow for the dynamic range required to operate with a feed from a solar process that essentially shuts down daily. Creating storage capacity of the synthesis gas and idling of the methanol trains may be used to decouple a response rate of the methanol synthesis plant from the response rate of the solar driven chemical reactor. The storage capacity and idling processes can be established for the integrated solar driven chemical plant to decouple a direct production rate of the synthesis gas generated in the solar driven chemical reactor from the supply requirements of the methanol synthesis plant. For example, solar produced, renewable, synthesis gas may be stored for multiple uses within the solar biorefinery. The stored gas is used to feed compressors during start-up, to buffer the gas clean up units during cloud events, and to feed the methanol synthesis reactor trains during start-up, cloud events, and during the night. The synthesis gas is stored within a pipeline in a fashion and utilizing technology very similar to that used by natural gas pipelines

[0067] In some embodiments, the methanol synthesis unit can be designed to handle 53% of the peak synthesis gas output from the solar reactor for the proposed site. An example plant, with appropriately sized storage, might run at near full capacity 24 hours per day during the summer months, utilizing daytime filled storage as necessary. The rest of the year the plant may respond to seasonal variations by tuning its production and storage rates to provide storage that allows for 24-hour operation at reduced throughput. There may still be weather events of extended length that can require

the warm idling of the methanol synthesis unit, and these can be managed through intelligent design of controls and reactor systems.

[0068] In one example, the methanol synthesis process can contain three reactor trains 254 that can operate in controlled synchronicity to provide the required dynamic range, including the capability to perform warm idles. Integrated control systems allow all portions of the plant to maintain high quality product output in the face of both expected and unexpected variations in solar energy. Process disruptions can be classified into three categories, each with its own control strategy: short-term fluctuation, nightfall, and large and extended change (including seasonal variation).

[0069] In the event of a short-term fluctuation, e.g., a variation or interruption in synthesis gas supply of several hours or less, synthesis gas may be supplied from storage and/or the methanol reactors are allowed to move within their dynamic range of stable operation.

[0070] When nightfall occurs, the methanol unit continues at constant operation at the output level selected by the control system, which can be based on the available storage and the season. In the summer, this can be at near 100% of design capacity, driven by long days and short nights. During the winter, throughput will generally be much lower to maintain steady operation over the course of the long night. Alternatively, during winter or low productivity times the storage can be filled to maximum and then feed to the synthesis operation at a rate that allows the synthesis operation to run at a steady rate for as long as possible before being re-idled and the storage cycle repeated.

[0071] In one embodiment, with adequate syngas storage, a reactor or suite of reactors may be operated within a narrow dynamic range. The output from the solar gasifier is initially routed straight to

storage. For example, in the early morning hours when syngas flow rates may be below the desired operational point of the reactor or reactor suite, the low volume flow would be routed straight to storage. After the storage reaches an appropriate level flow from the storage and/or gasifier is directed to the synthesis reactor which comes out of idle and operates at the desired operational point without going through a wide dynamic range operational ramp.

[0072] If a large and extended change in synthesis gas availability occurs, e.g. from extended weather or an unexpected shortage of stored synthesis gas, the control system directs a more pronounced response directing the reactor/s to their maximum combined turndown. In the case of three equal sized reactors, each with 50% turndown capability, that would be a combined system turn down to one sixth of maximum capacity. The control system determines, within stable operational limits, how to direct the parallel reactor trains to smoothly move to any output capacity within the wide dynamic range of the system. Consider, for example, a situation in which the entire system needs to run at 25% of design capacity. Two reactors would be warm idled and the remaining reactor would run at 75% of its capacity.

[0073] In one embodiment, the warm idle process can include using reactors that are isothermal boiling water shell and tube reactors with the catalyst packed in the tubes. The reactor shell can be well insulated. This configuration may help in maintaining a reactor at a warm idle and provide for rapid restarts. When the control system or plant operator commands a warm idle of a specific reactor in a methanol synthesis train, all reactor product effluent flow can be halted. This can be simultaneously accompanied with or followed by halting the reactor feed. The recycle flow may continue or may be idled. The reaction of internal gas may then proceed to equilibrium where it remains indefinitely.

[0074] The majority of this equilibrium composition is un-reacted hydrogen, which keeps the catalyst under a reducing atmosphere. There may be a decrease in pressure due to the consumption of a portion of the reactants. An externally fueled package boiler may be used to maintain the temperature of the liquid water that is bathing the reactor tubes, maintaining the catalyst at a process temperature that assures no condensation of products and will keep it in a condition to immediately respond to the restoration of fresh synthesis gas feed. Other portions of the reactor train, such as the insulated steam drum and the recycle pumps and line, may also be kept at temperature by the external boiler. The external boiler might be fueled with a variety of fuels including, for example, LPG, methanol, electricity, stored syngas, or natural gas. When it becomes time to bring the reactor out of the idle state, feed flow can be started at the lowest stable rate. If the recycle was not flowing during idle, the feed flow can be accompanied by or followed by the start of the recycle stream. The thermal mass of the reactor may heat enough of the incoming gas to initiate catalytic action, which accelerates the heating of the incoming recycle steam followed by external heating of the feed gas by the reactor effluent as the reactor returns to its operating condition.

[0075] In some embodiments, raw methanol, which includes 3 – 20% water, can be stored in, e.g., a 150,000-gallon tank that feeds the MTG gasoline conversion process. This liquid feed can decouple the MTG process from any of the cyclic solar process demands. The total storage capacity for a commercial plant can be sized based on feeder plant reliability and stability as well as down steam fuel transportation services. The storage size may be sized to allow the MTG plant to operate independently for whatever length of time is desired.

[0076] The storage tanks can follow standard industrial practices as to materials and construction. Each tank might reside above ground and sit within a lipped concrete apron that provides for capture and holding of unexpected spills or tank leaks allowing safe and environmentally appropriate mitigation to occur. Additionally, embodiments that convert the methanol to gasoline might also include a methanol-to-gasoline unit to convert the methanol to gasoline.

[0077] In some embodiments, a control system for the chemical reactor sends control signals to and receives feedback from a control system for the methanol synthesis plant. For example, some embodiments may use a control signal from the methanol plant just prior to idling a train is sent to the control system for the synthesis gas chemical reactor to boost the H2:CO molarity ratio. This can allow for time to alter synthesis gas composition including H2:CO ratio for methanol synthesis.

[0078] Figure 3 illustrates a diagram of an embodiment of a quenching via an injection of cooling medium into the reaction products, gas clean up, and particle and ash removal system 316. Direct quenching methods of cooling the hot reaction products via for example direct spraying of cooling mediums into the stream carrying the hot reaction products causing the cooling of the hot reaction products are discussed in Figure 3. Other example methods such as annular quenching methods of cooling the pipe carrying the hot reaction product from the solar driven reactor via heat transfer through the pipe are discussed, for example in Figure 4. Features described in one embodiment may be used in another embodiment.

[0079] The solar-driven chemical plant may directly cool the reaction products from the effluent stream out of the solar driven reactor. One or more spray nozzles in the quench zone 302 spray a

cooling fluid directly into the reaction product stream from the solar driven chemical reactor. In an embodiment where the cooling fluid is a liquid, the direct spraying of a liquid cooling fluid into the stream carrying the hot reaction products causes the liquid cooling fluid to vaporize into a gas. The liquid cooling fluid, such as water, becomes a superheated vapor, such as superheated steam, extracting the energy from the hot reaction products.

[0080] A control system can control one or more of the following plant parameters to ensure the temperature is at or below the desired cooled temperature, for example, 400 C, when leaving the quench zone 302. For example, the control system may control 1) changes a flow rate of a cooling medium being sprayed into the hot reaction products. Additionally, the control system may 2) provide feedback to change the flow rate of biomass into the solar driven chemical reactor. Additionally, the control system may 3) direct the concentrating field to change an amount of concentrated solar energy being directed at the aperture of solar thermal receiver. The control system may command a combination of some or all of the above.

[0081] Thus, the quench zone 302 may form near an exit of a gasification reaction zone in the reactor tubes of the chemical reactor and cool the effluent while not cracking or not thermally affecting the reactor tubes. Two or more of the multiple reactor tubes may form into a group at the exit. The group may combine their reaction products and un-reacted particles from the biomass gasification into a larger tube per group that forms a portion of the quench zone 302 or all of the tubes may supply the reaction products into a common manifold that forms a portion of the quench zone 302.

[0082] The one or more sprayers such as nozzles, valves etc., inside the quench zone 302 inject the cooling fluid directly into the reaction product synthesis gas stream to make the temperature

transition from the at least 1000 degree C to 800 degrees C or less within the 0.1-10 seconds to prevent metal dusting corrosion of the pipe walls.

[0083] A particle filter removal component 316 downstream of the quench zone 302 removes ash and other particles from the superheated gas and hot reaction products supplied from the quench zone 302. The particle filter removal component 316 can remove moisture as well as chemicals that may be harmful to the Rankine cycle engine. The hot reaction products and superheated gas can used as a medium to drive a Rankine cycle engine, such as a turbine, to draw the energy from the super heated vapor form of the cooling medium and hot reaction products. The Rankine cycle engine has an input to receive the hot reaction products and superheated gas. The super heated vapor form of the cooling medium and the hot reaction products after transferring their energy through the Rankine cycle change to a saturated vapor heavy in moisture content. The Rankine cycle engine may be inline with the process flow of the gas stream to directly receive the hot reaction products and superheated gas as the medium that drive the engine. A heat exchanger may also be inline with the process flow of the gas stream to directly receive the hot reaction products and superheated gas as the medium exact the energy from the gas stream and the hot effluent medium leaving the inline heat exchanger would drive the Rankine cycle engine.

[0084] Thus, the super heated vapor form of the cooling medium and hot reaction products after transferring their energy change states to a saturated vapor heavy in liquid. The saturated vapor flows through one or more knock out drums 312, 314 to dry the vapor, which then can run an organic turbine or transfer its energy via a steam condensing heat exchanger 304. Thus, the knockout drums 312, 314 located downstream of the Rankine engine remove

entrained water or other moisture from the synthesis gas stream supplied from the quench zone 302. Additional heat exchangers 308, 328 may also further cool the vapor.

[0085] In one embodiment, a solar-driven chemical reactor system includes a sulfur remediation unit 310 downstream of the quench zone 302. The sulfur remediation unit 310 can reduce an amount of sulfur present in a synthesis gas stream. Such a remediation unit 310 may reduce an amount of sulfur in a synthesis gas stream, containing at least the carbon monoxide and hydrogen molecules, from the gasification reaction down to a level below 50 ppb of sulfur in the synthesis gas stream.

[0086] A CO2 removal unit 318 sits behind the knockout drum and removes CO2 from the synthesis gas stream supplied from the quench zone 302. The CO2 content of the synthesis gas stream is reduced by the CO2 removal unit 318 to CO2 to less than 15% and a preferred range of 2-7 % of the synthesis gas stream. Also, a sulfur remediation unit 310 can be located downstream of the quench zone 302 to reduce an amount of hydrogen sulfide present in a synthesis gas stream. The synthesis gas stream may contain at least the carbon monoxide and hydrogen molecules from the gasification reaction down to a level equal to or below 100 ppb and preferably 50 ppb of sulfur. Additionally, an amine or other absorption/desorption like unit may remove both sulfur and CO2. However, if the sulfur levels are below the threshold due to sulfur removal via metal oxide particles being present in the reactor chemical reactor and/or quenching process, then an amine or other absorption/desorption like unit to remove both CO2 and sulfur might be replaced with just a CO2 filter.

[0087] In an embodiment, the sulfur remediation component 310 reduces an amount of sulfur present in a synthesis gas stream down

to a level equal to or below 100 ppm. The sulfur remediation component 310 may be located after the rapid quench zone 302 and the particle filter removal component but before the CO2 removal unit.

[0088] The synthesis gas coming to the compressors for storage or the methanol plant supply is high quality synthesis gas. The greater than 1000 degree C temperature of the reaction products from the chemical reactor is a high enough temperature for the greater than 90 percent conversion of the biomass particles to product gases and eliminates tar products to less than 200 mg/m^3 and preferably less than 50 mg/m^3. Also this renewable synthesis gas is an unusually clean because the sulfur level is controlled, CO2 removal occurs in the CO2 removal unit, water and other moisture removal occurs in the knockout drums, and particle filter removal occurs in the particle filter removal component.

[0089] In an embodiment, the synthesis gas can have total tar concentrations below 200 mg Nm-3, catalyst poison concentrations below 100 ppb for H2S, HCl, and NH3, and have a H2:CO ratio within the example range 2.3 to 2.7. These compositional concentration measurements can be taken periodically during gasifier operation through FTIR spectroscopy and gas chromatography periodically and measured with other detectors on a steady state basis. These parameters may be fed to the control system to ensure that synthesis gas composition does not vary (+/- 10%) from the desired composition, as well as to verify that catalyst poison concentrations are not above deactivation thresholds for the methanol synthesis catalyst. Ash measurements can be made one or more times daily and mass balances can be performed to ensure that overall biomass conversion remains above threshold targets and that alkali deposits are not being formed on the inside of the reactor.

[0090] The injection of the cooling fluid in the quench zone 302 may be controlled to also alter the chemical composition of the gas stream necessary to achieve the proper H2 to CO ratio of synthesis gas composition necessary for fuel synthesis, such as a 2:1 to 2.7:1 H2 to CO ratio. The controlled reactions may include one or more of the following example reactions.

[0091] 1) Water injects and mixes with the reaction product synthesis gas stream in order for an exothermic water gas-shift reaction to occur ($CO + H2O \rightarrow CO2 + H2 + energy$) for increasing hydrogen and decreasing carbon monoxide.

[0092] 2) Carbon dioxide is supplied with the natural gas entrainment gas, and/or generated in the biomass gasification reaction and becomes part of the reaction product synthesis gas stream in order for decreasing hydrogen and increasing carbon monoxide in an endothermic reverse water-gas shift reaction to occur ($CO2 + H2 + energy \rightarrow CO + H2O$).

[0093] 3) Methane, and low temperature water injects and mixes with the reaction product synthesis gas stream in the presence of a catalyst to drive the endothermic steam reformation of methane to occur ($CH4 + H2O + energy \rightarrow 3H2 + CO$) for increasing an amount of hydrogen relative to the carbon monoxide.

[0094] In some embodiments, the methanol trains have an input coupled to receive synthesis gas from an upstream solar driven chemical reactor. Additionally, a downstream fuel synthesis process can have its parameters controlled by the control system to account for the cyclic supply of solar generated synthesis gas as a feed product. For example, the controller may control parameters such as temperature, pressure, and chemistry of the fuel synthesis system during idle non-production periods of time so that the fuel synthesis system may rapidly resume when the supply of solar generated

synthesis gas resumes in sufficient quantities to perform fuel synthesis. For example, the fuel synthesis system may resume fuel synthesis within from 2 to 120 seconds and preferably within 10 seconds. In slower responding systems, the, the fuel synthesis system may resume fuel synthesis within from 10 minutes and 60 minutes depending upon how long the train has been idling and/or if all of the trains have been idling and now one or more are coming back to an operational state.

[0095] Figure 4 illustrates a diagram of an embodiment of a quenching, gas clean up, and ash removal system 400. A solar-driven chemical reactor system may include a solar thermal receiver aligned to absorb concentrated solar energy from one or more solar energy concentrating fields including 1) an array of heliostats, 2) solar concentrating dishes, and 3) any combination of the two.

[0096] An embodiment can include a solar driven chemical reactor that has multiple reactor tubes located inside the solar thermal receiver. In the multiple reactor tubes, particles of biomass may be gasified in the presence of a carrier gas in a gasification reaction. The gasification can produce reaction products that include hydrogen and carbon monoxide gas having an exit temperature from the tubes exceeding 1000 degrees C.

[0097] An embodiment may include one of 1) one or more apertures open to an atmosphere of the Earth or 2) one or more windows. The apertures or windows may be configured to pass the concentrated solar energy from the solar energy concentrating fields into the solar thermal receiver. The energy can impinge on the multiple reactor tubes and cavity walls of the receiver. Additionally, the reactor tubes serve the dual functions of 1) segregating the biomass gasification reaction environment from the atmosphere of the receiver and 2) transferring energy by solar radiation absorption

and heat radiation, convection, and conduction to the reacting particles. This energy may drive the endothermic gasification reaction of the particles of biomass flowing through the reactor tubes.

[0098] In an embodiment, a quench zone 402 immediately downstream of an exit of the chemical reactor may be used to immediately quench via rapid cooling of at least the hydrogen and carbon monoxide reaction products. The cooling might occur within 0.1-10 seconds of exiting the chemical reactor. Cooling to a temperature of 800 degrees C or less is possible. 800 degrees C is below a level to prevent metal dusting of some alloys if not cooled by the immediate quench. Additionally, the quench may prevent coalescence of ash remnants of the biomass particles.

[0099] An embodiment includes an exit of a gasification reaction zone in the reactor tubes of the chemical reactor. At the exit, the reaction products and un-reacted particles from the biomass gasification in the multiple tubes may be joined into several large tubes that form a portion of the quench zone 402. Additionally, a heat exchanger 404 can also form a part of the quench zone 402. A cooling fluid such as water/steam may be passed on an inside through heat exchanging tubes in the annular region of the quench zone 402 to cool the reaction product synthesis gas stream on the outside of the heat exchanging tubes. The cooling fluid may also be used to recuperate waste heat from the reaction product synthesis gas stream.

[00100] Additionally, in some embodiments, the reactor tubes that come out of the gasification reaction zone may be jacketed and make a temperature transition from the at least 1000 degree C to less than 400 degrees C. A cooling fluid, such as water/steam, may be passed through the jacket to cool the tubes containing the reaction product synthesis gas stream making the temperature transition. In another

embodiment, a quench zone 402 design may include dumping the reaction products from some or all the reactor tubes into a manifold and then into central single tube.

[00101] In an embodiment, a solar-driven bio-refinery may include an exit of a gasification reaction zone in the reactor tubes of the chemical reactor. The exit the reaction products and un-reacted particles from the biomass gasification in the multiple tubes can be dumped into a manifold and then into one or more synthesis gas tubes containing the reaction product synthesis gas stream of reaction products and un-reacted particles.

[00102] One or more injection pipes in the quench zone 402 can be located near the exit of the gasification reaction zone of the reactor tubes. In the quench zone 402 low temperature water (H2O), methane (CH4) with low temperature water and oxygen, and/or low temperature methanol (CH3OH) can be injected into the synthesis gas tubes and/or manifold. This can simultaneously 1) rapidly cool the reaction product synthesis gas stream from the at least 1000 degree C to less than 800 degrees C and 2) provide chemical compounds necessary to achieve a proper H2 to CO ratio of synthesis gas necessary for fuel synthesis. Additionally, the energy to cause the endothermic reactions may come from heat contained in the reaction product synthesis gas stream.

[00103] In some embodiments, a ratio from 2:1 to 2.7:1 H2 to CO may be desired. Various chemical compounds might be used to achieve the proper H2 to CO ratio of synthesis gas composition necessary for fuel synthesis. For example, water might be supplied and mixed with the hydrogen, carbon monoxide, and carbon dioxide in the reaction product synthesis gas stream. Using water with the hydrogen, carbon monoxide, and carbon dioxide may provide at least one of A) an exothermic water gas-shift reaction to occur (CO + H2O

→ CO2 + H2 + energy) for increasing hydrogen and decreasing carbon monoxide, and B) an endothermic reverse water-gas shift reaction to occur (CO2 + H2 + energy → CO + H2O) for increasing carbon monoxide and decreasing hydrogen. In another example, methane, low temperature water, and oxygen supplied and mixed with the reaction product synthesis gas stream may be used to drive the endothermic steam reformation of methane to occur (4CH4 + O2 + 2H2O + energy → 10H2 + 4CO). This can increase an amount of hydrogen relative to the carbon monoxide. Additionally, with either of the above H2 to CO ratio shifting reactions, later injecting low temperature methanol to further cool the synthesis gas and other reaction products traveling in the quench zone.

[00104] In one embodiment, after the reactor, the quench zone 402 injects via spraying water to obtain water gas shift stages (steam reformation) to increase CO production and for quenching between the temperature ranges of 450 C- 750 C. The process may cause both cooling and create the synthesis gas in the proper H2:CO ratio at the same time. In addition, the process may also feed biomass particles with steam and perform a water gas shift during the gasification reaction to obtain a 2:1 to 2.7:1 H2 to CO ratio and/or feed biomass particles with methane and perform steam reformation to obtain the 2:1 H2 to CO ratio.

[00105] The exothermic water-gas shift reaction (WGS Reaction) is a chemical reaction in which carbon monoxide reacts with water vapor to form carbon dioxide and hydrogen: CO + H2O → CO2 + H2. The endothermic RWGS produces the resultant H2 + CO molecules for the synthesis gas. (CO2 + H2 → CO + H2O) In another variant of the reverse water gas shift reaction, the chemical formula may be represented as (2 CO2 + 3 H2 + energy --→ 2 CO + 3 H2O). The RWGS may occur in the presence of a catalyst such as a Nickel alloy, Ni/Al2O3, etc. The exit synthesis gas from with the RWGS or

WGS, may then be immediately cooled/quenched in the quench zone to stabilize or otherwise capture the 2:1 ratio of H2 to CO.

[00106] In one embodiment, the solar-driven chemical reactor system may include a heat exchanger 404 forming part of the quench zone 402. One or more supply pipes may introduce a cooling medium with the reaction products. The heat exchanger 404 may introduced a cooled medium in one or more of a tail gas of N2, CO2, low temperature synthesis gas recycled from a storage tank, or other similar tail gas. Additionally, the reaction products may be cooled rapidly down to at least to 400 degrees C to prevent metal dusting in almost all alloys. Rapid quenching in the quench zone 402 may also prevents abrasive carbon formation. The reaction products may be cooled rapidly down to at least to 500 degrees C to prevent metal dusting in most alloys.

[00107] In some embodiments, a solar-driven chemical reactor system may include a Brayton engine to generate to electricity. In such a system, the quench zone 402 can have a cooling medium fed through a heat exchanger 404 to quench and cool the reaction products exiting the reactor. The heated cooling medium leaving the heat exchanger 404 uses recouped waste heat from the quench process to drive the Brayton engine to generate to the electricity 406. Additional heat exchangers 408 might also be used to provide additional cooling or drive the Brayton engine to generate to the electricity. Recuperated heat in a Brayton cycle engine may generate electrical power. For example, such an engine could run on air, other gases, or supercritical CO2, heated using waste heat, for example.

[00108] In an embodiment, a solar-driven chemical reactor system can include one or more cooling jackets. The reactor tubes that contain synthesis gas and other reaction products may be made of high temperature material. The reaction products contained in the

reactor tubes may make an initial transition in the quench zone 402 to a high temperature alloy, e.g., inconnel or similar alloy.

[00109] Once the temperature of the synthesis gas and other reaction products is low enough, the tubes carrying the synthesis gas can make a final transition to a low temperature material, such as stainless steel thru to carbon steel, etc. A cooling jacket can cover at least a portion of the reactor tubes, which aids in the quench and also allows the use of lower temperature tolerant transition materials to carry the synthesis gas and reaction products downstream of the chemical reactor in the quench zone 402.

[00110] An embodiment of the solar-driven chemical reactor system includes a pneumatic biomass feed system to feed the particles of biomass in a CO2 gas or steam carrier gas to the reactor tubes of the solar driven chemical reactor. A heat exchanger 404 in the quench zone 402 may be used to quench and cool the reaction products exiting the reactor tubes. Additionally, the heat exchanger 404 can be fed with a cooling medium. The cooling medium can carry waste heat away from the quenching exits the heat exchanger 404.

[00111] A counter flow heat exchange may be used to receive the cooling medium. Waste heat carried away by this cooling medium might be used to pre-heated the biomass particles are up to a maximum temperature of 400 degrees C prior to entry into the chemical reactor by the carrier gas. For example, the carrier gas can be heated by the cooling medium carrying the waste heat of the reaction products in the counter flow heat exchanger.

[00112] In an embodiment, the solar-driven chemical reactor system includes a pneumatic biomass feed system to grind and pulverize biomass to a particle size controlled to an average smallest dimension size between 50 microns (um) and 2000 um. These

particles may have a general range of between 200 um and 1000 um. Additionally, the pneumatic biomass feed system may supply a variety of non-food stock biomass sources fed as particles into the solar driven chemical reactor. The variety of non-food stock biomass sources can include three or more types of biomass that can be fed, individually or in combinational mixtures. Some examples of non-food stock biomass sources include rice straw, corn stover, switch grass, non-food wheat straw, miscanthus, orchard wastes, forest thinnings, forestry wastes, energy crops, source separated green wastes and other similar biomass sources. The biomass sources can be in a raw state or in a partially torrified state, as long as a few parameters, including particle size of the non-food stock biomass and operating temperature range of the reactor tubes are controlled including.

[00113] In one embodiment, a feed-forward and feedback control system can be configured to manage predicted changes in available solar energy as well as actual measured stochastic changes in available solar energy. The control system balances the gasification reaction between biomass feed rate and an amount of concentrated solar energy directed at the apertures or windows of the solar thermal receiver to the control temperature of the chemical reaction.

[00114] A control system can be used to balance operations of the reactors within the reactor suite to achieve a smoothly varying and wide dynamic range to accommodate seasonal and diurnal variations in feedstock availability. Reactors may be warm idled and/or restarted frequently and a multifaceted control system may be used to more quickly stabilize the output of a restarted reactor.

[00115] The system may control the temperature to keep the reaction temperature high enough for greater than 90 percent conversion of the biomass to product gases. The system may also

control the temperature to provide for elimination of tar products to less than 200 mg/m^3 and preferably less than 50 mg/m^3. Additionally, the temperature may also be controlled to keep it at a low enough reactor tube wall temperature to not structurally weaken the walls or significantly reduce receiver efficiency. For example, a temperature of less than 1600 degrees C might be used.

[00116] In an embodiment, the solar thermal receiver may have an indirect radiation driven geometry. For example, the indirect radiation driven geometry may be in the form of an absorbing, integrating cavity, of the solar thermal receiver. An inner wall of the cavity and the reactor tubes exchange energy primarily by radiation, not by convection or conduction. Exchanging energy primarily by radiation may allow for the reactor tubes to achieve a fairly uniform temperature profile even though the concentrated solar energy is merely directly impinging on the reactor tubes from one direction. Additionally, the radiation heat transfer from the inner wall and the reactor tubes can be the primary source of energy driving the gasification reaction in which the small biomass particles act as millions of tiny absorbing surfaces of radiant heat energy coming from the inner wall and the tubes.

[00117] In an embodiment, the solar driven chemical reactor can have a downdraft geometry. Such a geometer has multiple reactor tubes in a vertical orientation. These tubes are located inside the solar thermal receiver. Additionally, the multiple reactor tubes in this chemical reactor design increase available reactor surface area for radiative exchange to the biomass particles as well as inter-tube radiation exchange. The tubes may also function to isolate a reacting environment inside the tubes from the cavity receiver environment outside the tubes. In some embodiments, high heat transfer rates of the walls and tubes allow the particles biomass to achieve the high enough temperature necessary for substantial tar destruction and

complete gasification of greater than 90 percent of the biomass particles into reaction in a very short residence time between a range of 0.01 and 5 seconds.

[00118] In an embodiment of a downdraft geometry, the biomass particles fall through the downdraft reactor to substantially eliminate an undesirable build-up of product on the tube walls in the reaction zone. Buildup could lead to reduced heat transfer and even clogging of the tube because of the pressure and gravity pulling the particles through the reaction zone of the reactor tube. Additionally, low surface area to volume ratios may provide less surface area for the material to sticking. In some embodiments, ash fusion and deposition may not be a problem due to short residence time in some downdraft reactor systems.

[00119] In one embodiment, a solar-driven chemical reactor system includes an ash and particle storage mechanism. In such a system, un-reacted biomass particles and ash remnants of the biomass exit the solar driven chemical reactor at the greater than 1000 degrees C.

[00120] A separator may be configured to separate the particles and ash remnants from the gas products of the reaction products into the ash and particle storage mechanism. Some example systems may store these un-reacted biomass particles and ash remnants to extract their heat, This heat may be used to heat a working fluid, gaseous, or solid medium that drives an electricity generation apparatus or other apparatus used in doing heat based processes such as thermodynamic work, preheating water, preheating gas streams, etc.

[00121] In one embodiment, a solar-driven chemical reactor may include a sulfur removal sorbent 410. The sulfur removal sorbent 410 may be present in the biomass gasification process or initially

introduced in the quench zone, to reduce an amount of sulfur present in a synthesis gas stream exiting the quench zone.

[00122] In one embodiment, a series of sintered porous stainless steel metal filters 412, 414 to remove particulates from the synthesis gas stream exiting the quench zone may be used. The particulates can be sent to an ash holding vessel. In such a vessel the particulates can be staged for removal to be used as a soil additive, as the particulates contain only biologically derived materials and gypsum from the sulfur removal sorbent.

[00123] In one embodiment, a solar-driven chemical reactor system includes a sulfur remediation unit 410 downstream of the quench zone 402. The sulfur remediation unit 410 can reduce an amount of sulfur present in a synthesis gas stream. Such a remediation unit 410 may reduce an amount of sulfur in a synthesis gas stream, containing at least the carbon monoxide and hydrogen molecules, from the gasification reaction down to a level below 50 ppb of sulfur in the synthesis gas stream.

[00124] In one embodiment, a dual stage cyclone filters can be located before the sulfur remediation unit to allow un-reacted biomass recycling with cyclone separation. A first heavy cyclone stage can be constructed to remove heavy particles and a second lighter cyclone stage can be constructed to remove lighter particles consisting mainly of un-reacted biomass. The substantially particle-free synthesis gas then passes into the sulfur remediation unit.

[00125] In one embodiment, a solar-driven chemical reactor system may include a synthesis gas stream including the carbon monoxide and hydrogen molecules that come out from the quench zone 402. A knockout drum may be located downstream of the quench zone. The knockout drum may be used to remove entrained water from the synthesis gas stream supplied from the quench zone.

[00126] A particle filter removal component 416 may be located downstream of the quench zone 402 where ash and other particles are removed from the synthesis gas stream supplied from the quench zone. Additionally, a CO2 removal unit 418, such as an amine acid gas removal unit, may sit behind the knockout drum. Such a CO2 removal unit 418 removes CO2 from the synthesis gas stream supplied from the quench zone. For example, CO2 content of the synthesis gas stream may be reduced by the CO2 removal unit to CO2 being less 5% of the synthesis gas stream.

[00127] Figure 5 illustrates a diagram of an embodiment of a multiple stage compressor system. In such a system, a solar driven reactor 502 for synthesis gas can produce synthesis gas from bio-particles using solar energy to break down the bio-particles. A compressor set 504, 510, 512 pressurizes synthesis gas in different stages in the plant. For example, some embodiments might include at least three stages of compressors 504, 510, 512. A first low-pressure stage 504 may be located in a synthesis gas clean up portion of a system just prior to an amine step. The low-pressure stage may be less than 750 PSIG. In other embodiments, the low-pressure stage may be less than 250 PSIG. In still other embodiments, the low-pressure stage may be less than 100 PSIG. The first compressor 504 feeds the synthesis gas stream to the COS cleanup 506 and CO2 and sulfur remediation units 508, such as an amine plant. The pressure may be for example 100 PSIG.

[00128] A higher pressure 750-1200 PSIG stage 510 for injecting cleaned up solar generated synthesis gas into a common input into the methanol process may be located. The second compressor 510 directly feeds synthesis gas to a methanol synthesis unit and brings the pressure to that required for methanol synthesis.

[00129] The third stage compressor 512 may be used for pumping excess synthesis gas from the solar chemical reactor into a high pressure 2000-3000 PSIG storage tank. Generally, the compressor will re-circulate synthesis gas from the storage tank 516 as a way to maintain an idle state but be ready to operate 24 hours a day.

[00130] A synthesis gas storage unit 516 may exist to account for diurnal events placed before a CO2 and sulfur removal plant 508. The synthesis gas storage buffer 516 before the CO2 and sulfur plant 508 allows for the CO2 and units to be significantly smaller in size/capacity. For example, the synthesis gas storage unit 516 is sized to handle peak daytime synthesis gas flow for the location of the system, whereas the CO2 and sulfur unit 508 removes CO2 and sulfur to required levels for synthesis of methanol and may be sized for 50-85% flow. The synthesis gas may be re-circulated through these CO2 and sulfur remediation units 508 to place the sulfur and CO2 levels in the synthesis gas into acceptable limits. In an embodiment, the synthesis gas storage unit 516 is sized to operate the methanol synthesis plant 514 for 1 hour at 100 percent peak output without receiving supplemental synthesis gas coming out of the solar driven chemical reactor 502.

[00131] The synthesis gas exits the storage vessels 516 or the synthesis gas compressor 510 to enter the methanol synthesis unit 514. Methanol is a chemical with formula CH3OH (often abbreviated MeOH). It is the simplest alcohol, and is a flammable fuel and can be stored as a liquid at normal temperatures. In one example of methanol synthesis, the Carbon monoxide, Carbon dioxide, and hydrogen in synthesis gas react on a catalyst to produce methanol. A widely used catalyst is a mixture of copper, zinc oxide, and alumina. As an example, at 5–10 MPa (50–100 atm) and 250 °C, it

can catalyze the production of methanol from the carbon oxides and hydrogen with high selectivity according to the overall reaction:

$CO + 2\ H_2 \rightarrow CH_3OH$

[00132] The methanol synthesis consumes 2 moles of hydrogen gas for every mole of carbon monoxide. One way of dealing with the excess hydrogen if it exists is to inject carbon dioxide into the methanol synthesis reactor, where it, too, reacts to form methanol according to the overall equation:

$CO_2 + 3\ H_2 \rightarrow CH_3OH + H_2O$

[00133] In an embodiment, the control system may supply synthesis gas with higher amount of CO2 when the trains are running and no idling is expected. However, the control system may supply synthesis gas with lower amount of CO2 and H2 rich ratio when idling of the methanol reactor plants is anticipated.

[00134] The methanol synthesis unit 514 may consist of standard shell and tube Lurgi style methanol reactors. This is a well-known process and is operated on very large scales (millions of gallons of methanol per year) worldwide. However, this methanol synthesis unit 514 may be operated on a cyclic basis. The methanol synthesis process operates at an example 4:1 recycle ratio and converts 96% of the synthesis gas to methanol. The raw methanol is distilled from the entrained water product and fed to a standard methanol-to-gasoline (MTG) unit, where an example 97% of the methanol is converted to gasoline and LPG, with a ratio of 4.8 gallons of gasoline per gallon of LPG. The LPG and C-2 hydrocarbons can be burned to preheat the recycle stream in the MTG plant and to generate electricity to support plant operations. Additionally, methanol may be stored in methanol storage 518 or re-circulated as needed, for example, when idling.

[00135] As discussed above, multiple methanol reactor trains can be operated in parallel from a common input of 1) synthesis gas from either 1) a solar driven chemical reactor and 2) synthesis gas from a storage tank or a combination of both. The fuel synthesis portion of the control system controls the operation of the multiple trains by potentially idling one or more of the methanol reactor trains based on feedback from the amount of synthesis gas being generated by the solar driven chemical reactor, which is subject to marked variations in volume of synthesis gas output based on a seasonal, diurnal and weather effects. Thus, the multiple methanol reactor trains are individually controllable to be cycled between the idle state and the operational state due to the variable amount of synthesis gas being fed into the process from the solar driven chemical reactor.

[00136] The downstream fuel synthesis process can have its parameters controlled to account for the cyclic supply of solar generated synthesis gas as a feed product. Thus, the methanol synthesis control system may control parameters including chemistry, temperature, and pressure of the methanol synthesis plant during idle non-production periods of time so that the methanol synthesis plant may rapidly resume to generating product methanol when the supply of solar generated synthesis gas resumes in sufficient quantities. Additionally, the methanol synthesis control system may control parameters including chemistry, temperature, and pressure of the methanol synthesis plant during idle non-production periods of time so that the methanol synthesis plant has little to no loss in catalytic activity or throughput over the plant's lifetime. This allows for the protection of the catalyst, as long as the synthesis gas and product methanol gas are kept at a certain temperature and pressure, then the gases remains vaporized and does not condense on the catalyst prolonging the life of the catalyst.

[00137] As discussed, the multiple methanol reactor trains may be operated in parallel from an input supplied with syngas from either 1) the solar driven chemical reactor 2) from a syngas storage unit, or a combination of both. The operation of the multiple trains is controlled by potentially 1) idling one or more of the methanol reactor trains or 2) reducing the output of one or more of the methanol reactor trains based on feedback from the amount of synthesis gas being generated by the solar driven chemical reactor, which is subject to marked variations in volume of syngas output based on a seasonal, diurnal and weather effects. Thus, the multiple methanol reactor trains are individually controllable to be cycled between the idle state and some percentage of maximum throughput in the operational state due to the variable amount of syngas being fed into the process from the solar driven chemical reactor.

[00138] In some embodiments, wide dynamic range compressor use in solar bio-refineries can be used. A suite of compressors, with their appropriate control system(s), can allow for flexible wide range turn down. Compressors may use re-circulation and other strategies as well as direct turndown to achieve a flexible suite output. Additionally, compressors may be of various sizes and may be organized in both a serial and parallel fashion to achieve the compression pressure and volume required.

[00139] In some embodiments, a controller may be used to control operation of the multiple methanol trains. For example, the control system may potentially idle one or more of the methanol reactor trains based on theamount of synthesis gas being generated by the solar driven chemical reactor. The amount of synthesis gas being generated is subject to marked variations in volume of synthesis gas output based on a seasonal, diurnal and weather effects. Accordingly, the multiple methanol reactor trains are idled as

needed based on a variable amount of synthesis gas fed into the process.

[00140] In some embodiments, the controller may control various parameters including temperature and pressure during cyclic operation of the fuel synthesis system, including cyclic operation of the methanol synthesis plant. This may provide for little to no loss in catalytic activity or throughput over the plant's lifetime allowing for the protection of the catalyst. For example, the catalyst may be protected by keeping the synthesis gas and product methanol gas at a certain temperature and pressure such that the gases remain vaporized and does not condense on the catalyst, prolonging the life of the catalyst.

[00141] In some embodiments, the control system comprises control algorithms that control reactor operation. For example, the control algorithms may allow rapid and efficient reactor cycling by using synthesis gas from a solar driven chemical reactor. The control algorithms may use synthesis gas from a storage tank to allow for rapid and efficient reactor cycling. The control algorithms may also use recycling synthesis gas and methanol product gas from the outlet of the reactor trains to keep at least one of the trains operating at some percent of its maximum throughput. Additionally, the control system may also keep any idle reactors at or near reaction temperature and pressure during the daily operation. The compressor control system can also be designed for using different types of compressors, operating compressors at potentially different pressure, etc.

[00142] The control system may also control parameters including temperature, pressure, and chemistry of a fuel synthesis system during idle non-production periods of time so that the fuel synthesis system may rapidly resume fuel product when the supply of

solar generated synthesis gas resumes in sufficient quantities to perform fuel synthesis. Additionally, in some embodiments, the control system may control compressors in a fuel synthesis system. This can assist in controlling pressure in the cyclic operations.

[00143] In some embodiments, the control system may control temperature of a reactor train when the reactor train is temporarily idled. This can be done so that an idled reactor is kept at or near a reaction temperature with heat makeup as required to offset heat losses. These losses might be offset using heat from boiling water heated from an external boiler or with heat from the methanol synthesis reaction.

[00144] In some embodiments, the control system controls a temperature of a reactor train when the reactor train is temporarily idled, such that the idled reactor is kept at or near a reaction temperature with waste heat from other areas of the plant including the quenching operation on the synthesis gas coming out of the solar driven chemical reactor.

[00145] It will be understood by those of skill in the art that the multiple parallel methanol reactor trains and the control system described above is an example system. The systems and methods described herein may also be applied to Fischer-Troupe processes, solid chemistry approaches, etc. to, for example, provide for cyclic operation. Accordingly, in other embodiments, Fischer-Troupe processes, solid chemistry approaches, etc., may include multiple parallel reactors and these reactors might be kept at or near reaction temperature and pressure when idle to allow for a quicker startup. Additionally, various storage devices might be used to allow for recirculation of materials during idling periods.

CLAIMS

What is claimed is:

We claim:

1. A fuel synthesis system comprising:

a multiple methanol reactor train, operated in parallel from a supply input of 1) synthesis gas from a solar driven chemical reactor and 2) synthesis gas from a storage unit, or 3) a combination of both, wherein the multiple methanol reactor trains are idled as needed based on a variable amount of synthesis gas fed into the process; and

a controller to control operation of the multiple methanol trains by 1) idling one or more of the methanol reactor trains, 2) altering an output amount being generated by one or more of the methanol reactor trains, 3) switching one or more of the methanol reactor trains to an operational state and 4) any combination of the three, based on an amount of synthesis gas being generated by the solar driven chemical reactor, which is subject to marked variations in volume of synthesis gas output based on seasonal, diurnal and weather effects.

2. The fuel synthesis system of claim 1, wherein the multiple methanol reactor trains are physically separate reactor trains, wherein the physically separate reactor trains are in parallel, and wherein the control system controls parameters including temperature, pressure, and chemistry of the fuel synthesis system during idle non-production periods of time so that the fuel synthesis system may rapidly resume fuel production when a supply of solar generated synthesis gas resumes in sufficient quantities to perform fuel synthesis.

3. The fuel synthesis system of claim 1, wherein the multiple methanol reactor trains comprise a common reactor with a manifold

that feeds multiple virtual reactor trains from the manifold; and wherein the multiple methanol reactor trains are incased in the shell of the common reactor.

4. The fuel synthesis system of claim 1, wherein the methanol trains have an input coupled to receive synthesis gas from the upstream solar driven chemical reactor, wherein the control system controls parameters of a downstream fuel synthesis process to account for the cyclic supply of solar generated synthesis gas as a feed product, wherein the controller controls parameters including temperature, pressure, and chemistry of the fuel synthesis system during idle non-production periods of time so that the fuel synthesis system may rapidly resume fuel production when the supply of solar generated synthesis gas resumes in sufficient quantities to perform fuel synthesis, and wherein the controller controls the parameters during cyclic operation of the fuel synthesis including cyclic operation of the methanol synthesis plant with little to no additional loss in catalytic activity or throughput over the plant's lifetime above expected losses from the catalyst aging and participating in the catalytic activity, by protecting the catalyst, through 1) keeping the synthesis gas and product methanol gas at a certain temperature and pressure such that the gases remain vaporized and do not condense on the catalyst, prolonging the life of the catalyst and 2) maintaining a chemically reducing atmosphere for the catalyst.

5. The fuel synthesis system of claim 1, wherein a reactor is a shell and tube reactor and when the reactor train is idled, the temporarily idled reactor is kept at or near the reaction temperature with heat makeup as required to offset heat losses 1) with heat from a boiling water heated from an external boiler and 2) with heat from the methanol synthesis reaction, or 3) any combination of the two; and wherein the shells of each reactor train are interconnected such

that a hot working fluid removing the exothermic heat from a train that is operating is circulated around an idle train to keep the idle trains near reaction temperature and the reactor uses layers of insulation around the methanol reactor train to keep the plant near reaction temperature.

6. The fuel synthesis system of claim 1, wherein, when a reactor train is idled, the temporarily idled reactor train is kept at or near the reaction temperature with waste heat from other areas of the plant including a quenching operation on the synthesis gas coming out of the solar driven chemical reactor; and

wherein the waste heat is stored in a 1) a hot solid, heated liquid, or heated vapor, where the waste heat is generated during the operation of the solar driven reactor when sunset or weather events are not blocking the Sun.

7. The fuel synthesis system of claim 1, wherein, before a reactor train is idled the H2 content inside the methanol reactor is boosted by adding synthesis gas with a higher ratio of H2:CO from the solar driven reactor, or adding supplemental H2 from an H2 storage supply, to ensure that a reducing atmosphere is maintained within the reactor.

8. The fuel synthesis system of claim 1, wherein the multiple methanol reactors comprise at least two methanol reactors that are operable at a percentage of maximum throughput such that the fuel synthesis system has a dynamic operating range of at least 16 to 100 percent of capacity.

9. The fuel synthesis system of claim 1, wherein the control system comprises control algorithms that control reactor operation, the control algorithms specifically allowing rapid and efficient reactor

cycling by 1) using synthesis gas from the solar driven chemical reactor, 2) synthesis gas from the storage unit, and 3) recycling synthesis gas and methanol product gas from the outlet of the reactor trains to keep at least one of the trains operating at some percent of its maximum throughput; and wherein the control system keeps an idle reactors at or near reaction temperature and pressure during the daily operation.

10. The fuel synthesis system of claim 1, wherein the control system controls compressors in the fuel synthesis system to assist in controlling pressure in a cyclic operation, wherein the system comprises at least three levels of compression, a low-pressure level, of less than 500 PSIG in a synthesis gas clean up portion of a system just prior to a CO2 remediation unit, a higher intermediate pressure 500-1500 PSIG level for injecting cleaned up solar generated synthesis gas from the solar driven chemical reactor into an input into the methanol synthesis process, and a third level of compression for pumping excess synthesis gas from the solar chemical reactor into the storage unit at a pressure greater than the intermediate pressure.

11. The fuel synthesis system of claim 10, wherein the storage unit comprises at least one of a pipeline or other underground storage structure.

12. The fuel synthesis system of claim 10, further comprising a flywheel drive mechanism including a flywheel sized such that it can store enough rotational energy to start a compressor and small enough to be started and accelerated using less power than is needed to start the compressor; a low power starting mechanism for starting and then accelerating the flywheel, the low power starting mechanism providing enough power to rotate the flywheel, but less power than is needed to start the compressor, wherein the speed of

the flywheel builds over time as power is received from the low power starting mechanism; and a mechanism to couple the fly wheel to the compressor such that rotational energy from the fly wheel can be transferred to the compressor to start the compressor.

13. A control system for a fuel synthesis system comprising control algorithms on reactor operation, the control algorithms specifically allowing rapid and efficient reactor cycling by 1) using synthesis gas from a solar driven chemical reactor, 2) synthesis gas from a storage unit, and 3) recycling synthesis gas and methanol product gas from the outlet of the reactor trains to keep at least one of the trains operating at some percent of its maximum throughput; and wherein the control system keeps an idle reactor at or near reaction temperature and with a pressure change of no more than 30% during the idle periods.

14. The control system of claim 13, further comprising a system that controls compressors in a fuel synthesis system to assist in controlling pressure in the cyclic operations, wherein the system comprises at least two levels of compression, a first pressure 750-1200 PSIG level for injecting cleaned up solar generated synthesis gas into a common input into the methanol synthesis process, and a second level of compression for pumping excess synthesis gas from the solar chemical reactor into the storage unit, where the high pressure is defined as being greater than the second level of compression.

15. The control system of claim 13, wherein the system controls operation of multiple methanol trains by 1) idling one or more of the methanol reactor trains and/or 2) reducing an output amount being generated by one or more of the methanol reactor trains based on the amount of synthesis gas being generated by the solar driven

chemical reactor, which is subject to marked variations in volume of synthesis gas output based on a seasonal, diurnal and weather effects; and wherein the multiple methanol reactor trains are idled or set at a reduced output as needed based on a variable amount of synthesis gas fed into the process.

16. The control system of claim 13, wherein the control system controls parameters including temperature, pressure, and chemistry of a fuel synthesis system during idle non-production periods of time so that the fuel synthesis system may rapidly resume fuel production when the supply of solar generated synthesis gas resumes in sufficient quantities to perform fuel synthesis.

17. The control system of claim 13, wherein the control system controls parameters including temperature, pressure, and chemistry of a fuel synthesis system during cyclic operation of the fuel synthesis including cyclic operation of the methanol synthesis plant with little to expected typical loss in catalytic activity or throughput over the plant's lifetime allowing for the protection of the catalyst, by keeping the synthesis gas and product methanol gas at a certain temperature and pressure such that the gases remain vaporized and do not condense on the catalyst, prolonging the life of the catalyst.

18. The control system of claim 13, wherein the control system controls a temperature of a reactor train when the reactor train is temporarily idled, such that the idled reactor is kept at or near a reaction temperature with heat makeup as required to offset heat losses with one or more of 1) heat from boiling water heated from an external boiler, 2) heat from the methanol synthesis reaction from another methanol reactor that is operating, 3) an internal electric

heater or a combination of all three, where the operation of the external boiler controlled by the control system.

19. The control system of claim 13, wherein the control system controls a temperature of a reactor train when the reactor train is temporarily idled, such that the idled reactor is kept at or near a reaction temperature with waste heat from other areas of the plant including the quenching operation on the synthesis gas coming out of the solar driven chemical reactor.

20. A method for an integrated solar driven chemical plant, comprising:

conducting a chemical reaction in a solar driven chemical reactor having multiple reactor tubes using concentrated solar energy to drive the conversion of the chemical reactant, wherein an endothermic chemical reaction conducted in the reactor tubes includes one or more of the following: biomass gasification, steam methane reforming, methane cracking, using solar thermal energy coming from a concentrated solar energy field;

supplying the products from the chemical reaction for a catalytic conversion of the products from the solar driven chemical reaction into a hydrocarbon fuel or other chemical in a chemical synthesis plant; where an operation of the chemical synthesis plant is dependent upon an amount of product generated in the solar driven chemical reactor; and

a control system for the chemical synthesis plant is configured to send control signals to and receiving feedback from a control system for the chemical reactor, and the control system for the chemical reactor at least indicates the amount of product being generated in the solar driven chemical reactor.

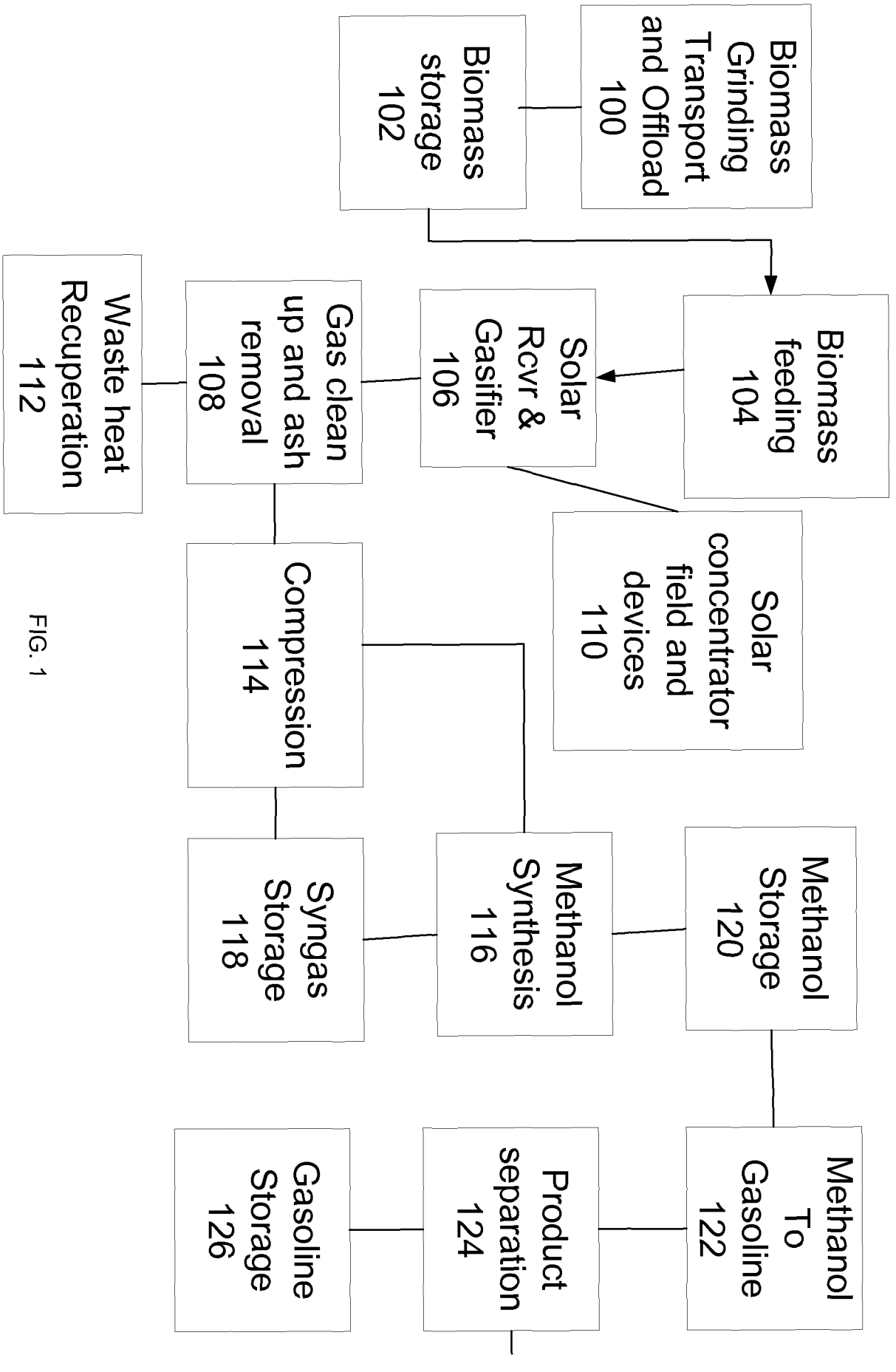

Biomass Grinding Transport and Offload 100
Biomass storage 102
Biomass feeding 104
Solar Rcvr & Gasifier 106
Gas clean up and ash removal 108
Waste heat Recuperation 112
Solar concentrator field and devices 110
Compression 114
Syngas Storage 118
Methanol Synthesis 116
Methanol Storage 120
Methanol To Gasoline 122
Product separation 124
Gasoline Storage 126

FIG. 1

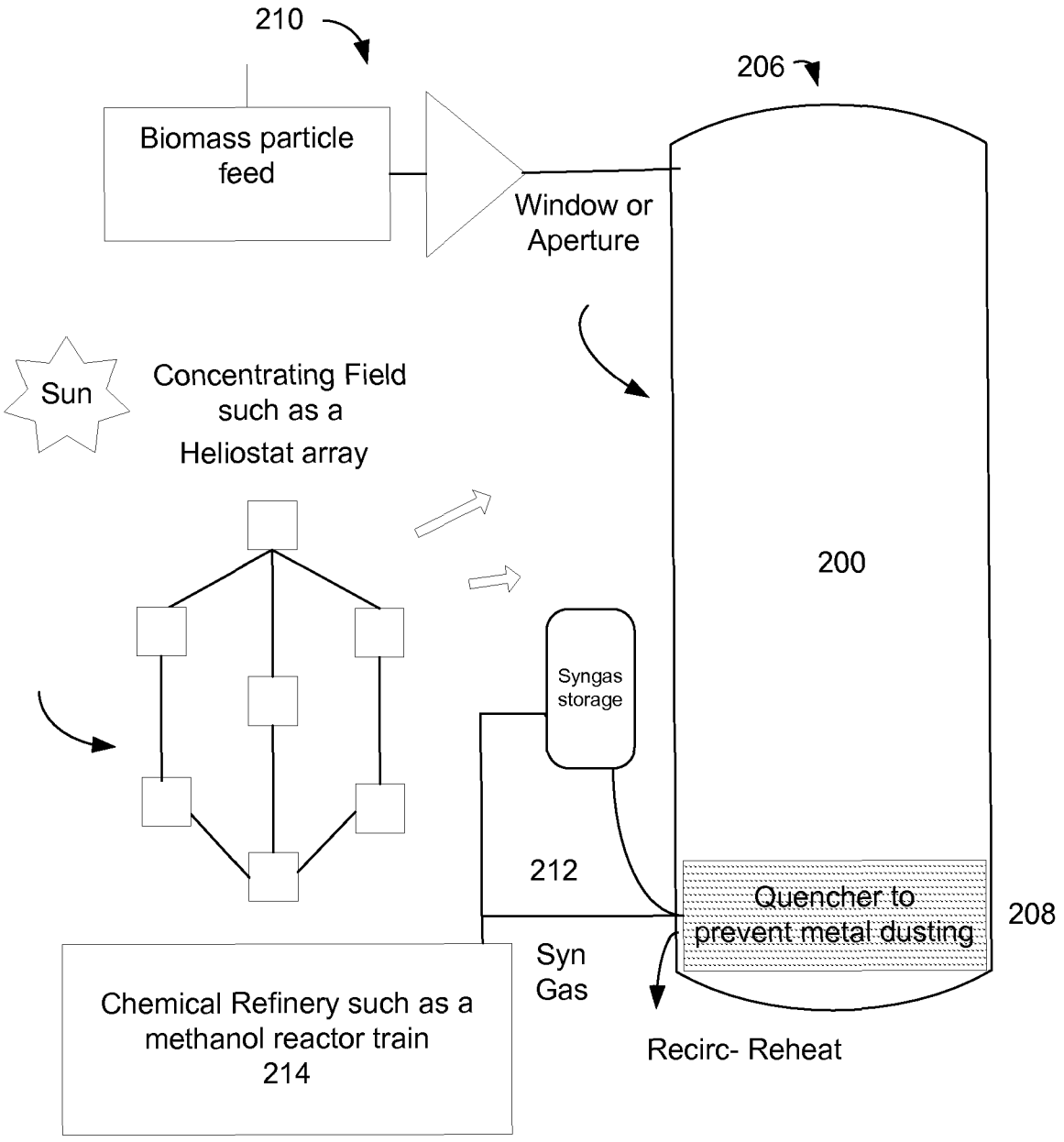

210
206
Biomass particle feed
Window or Aperture
Sun
Concentrating Field such as a Heliostat array
200
Syngas storage
212
Quencher to prevent metal dusting
208
Syn Gas
Chemical Refinery such as a methanol reactor train 214
Recirc- Reheat

FIG. 2A

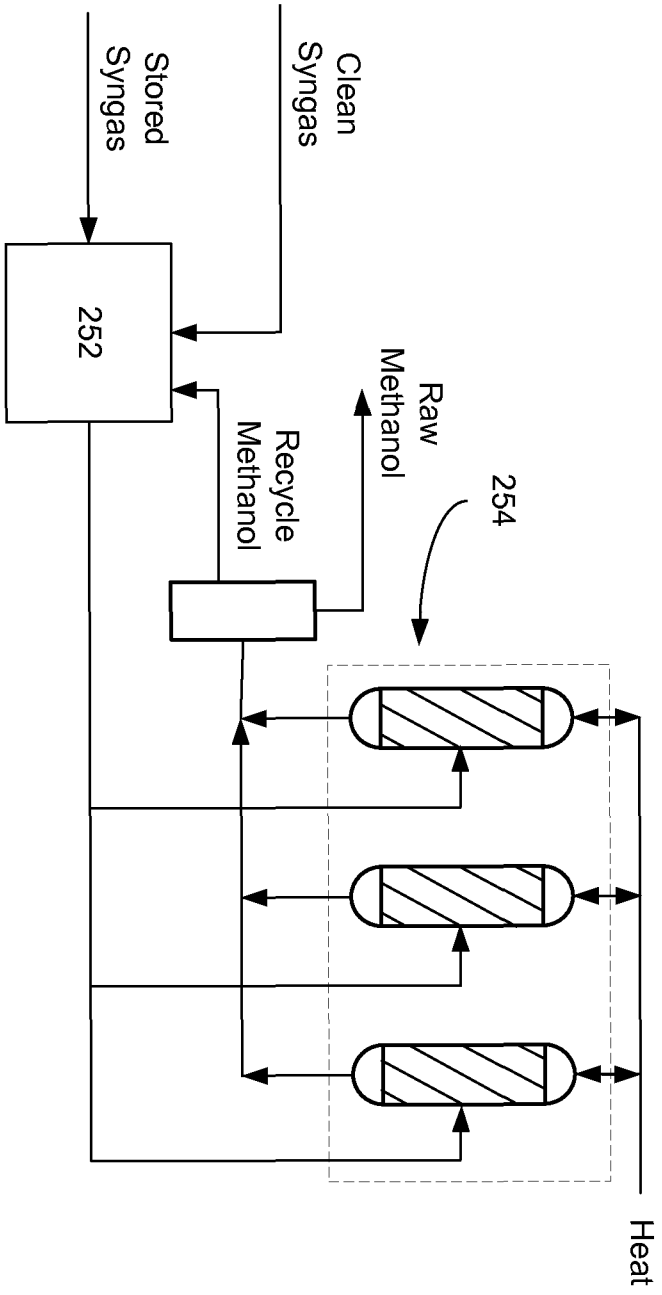

250
Stored Syngas
Clean Syngas
252
Recycle Methanol
Raw Methanol
254
Heat

FIG. 2B

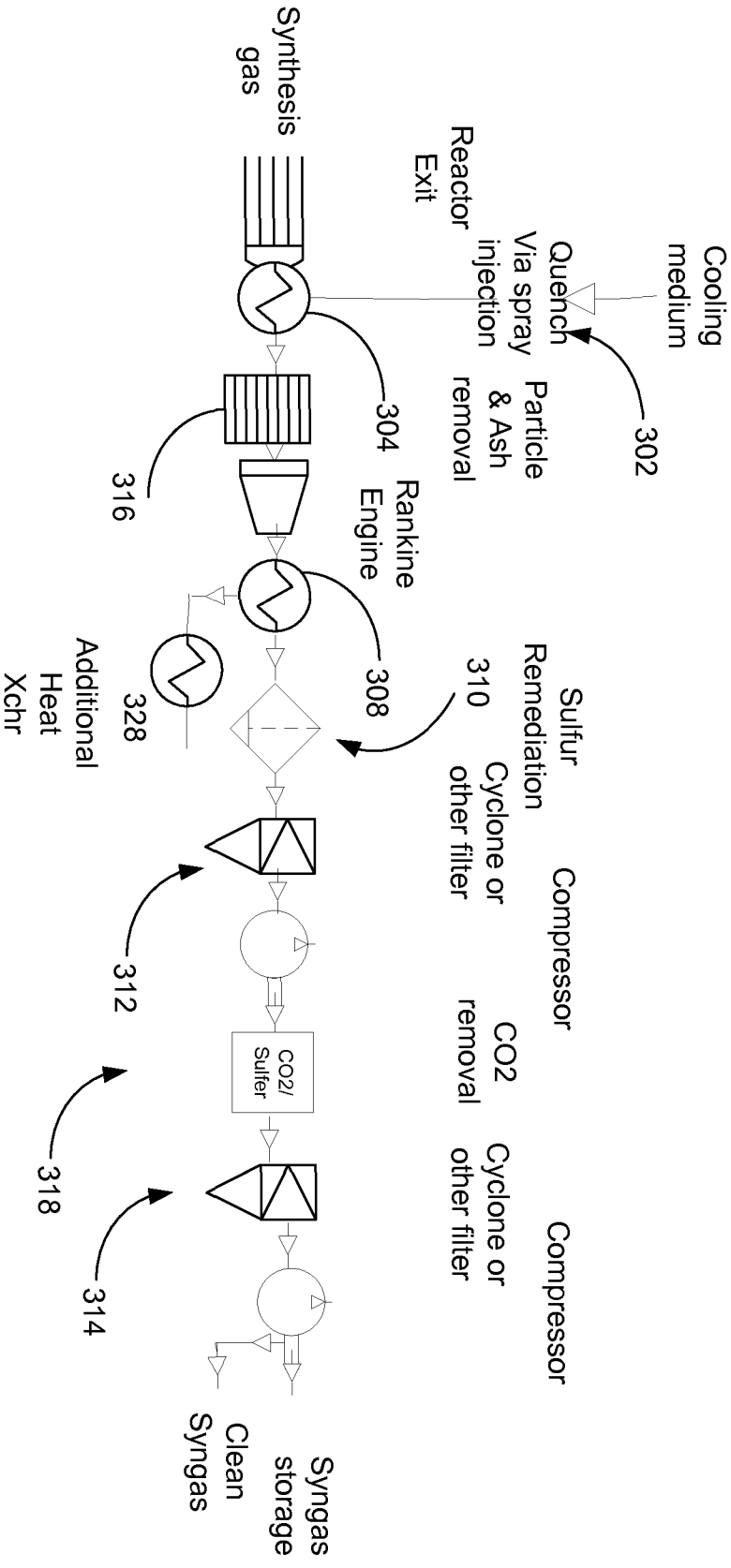

300
Synthesis gas
Reactor Exit
Quench Via spray injection
Cooling medium
302
304
Particle & Ash removal
316
Rankine Engine
308
328
Additional Heat Xchr
Sulfur Remediation
310
Cyclone or other filter
Compressor
312
CO2 removal
CO2/ Sulfer
318
Cyclone or other filter
Compressor
314
Clean Syngas
Syngas storage

FIG. 3

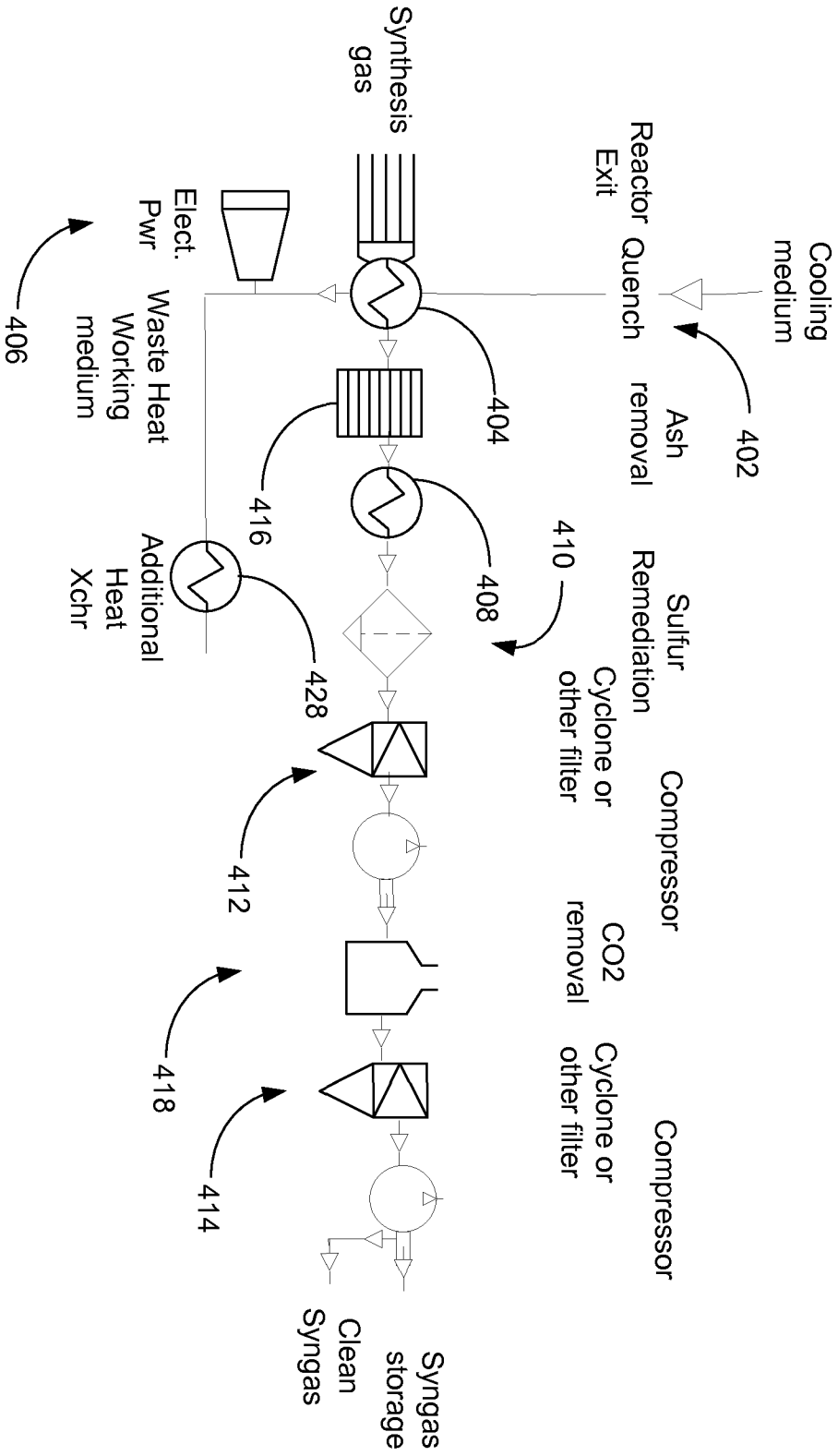

400
Cooling medium
402
Reactor Exit
Quench
Ash removal
404
Synthesis gas
Elect. Pwr
Waste Heat
Working medium
406
416
Additional Heat Xchr
408
Sulfur Remediation
410
Compressor
Cyclone or other filter
428
412
CO2 removal
Compressor
Cyclone or other filter
418
414
Syngas storage
Clean Syngas

FIG. 4

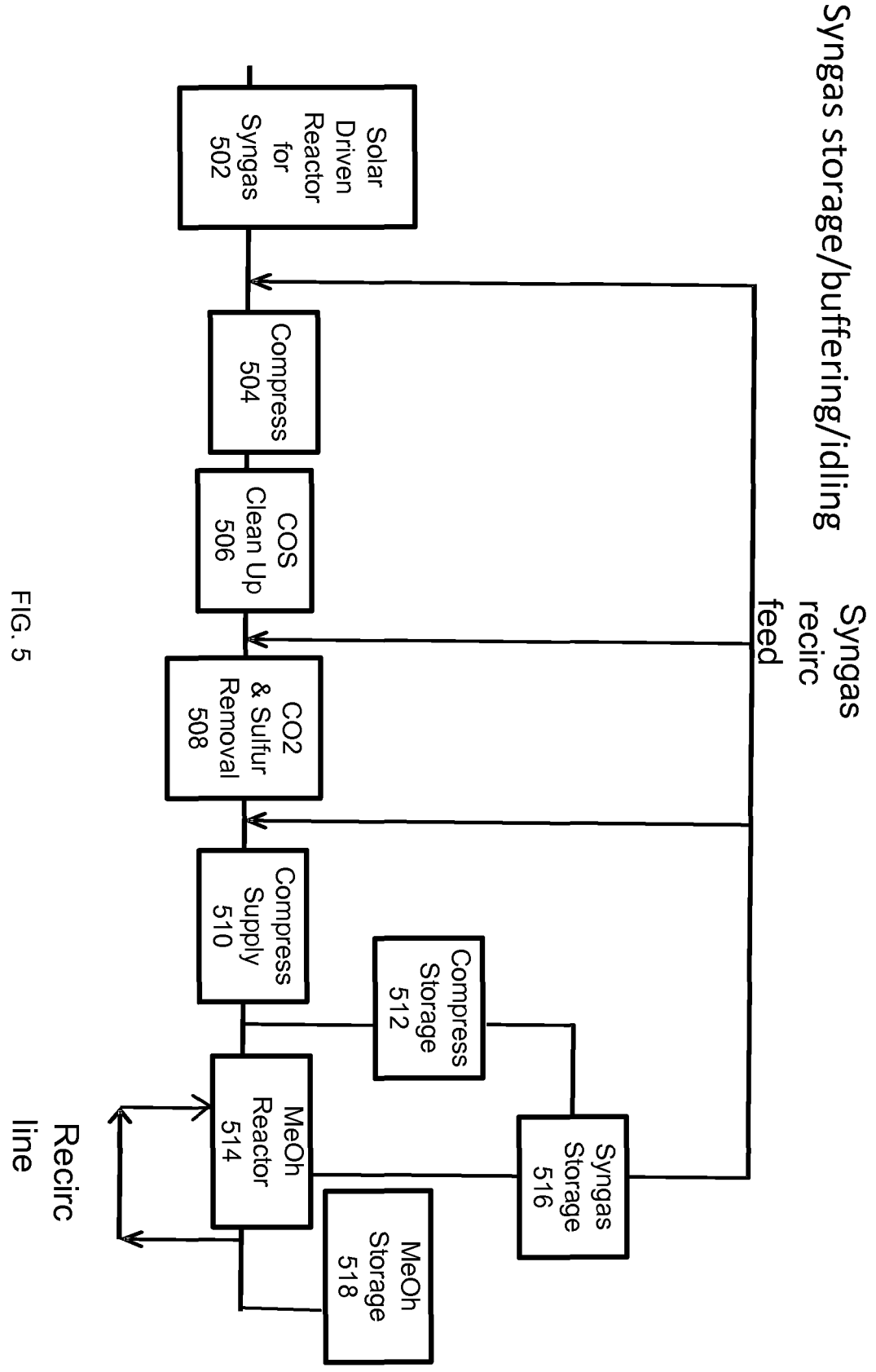

Syngas storage/buffering/idling
Syngas recirc feed
Solar Driven Reactor for Syngas 502
Compress 504
COS Clean Up 506
CO2 & Sulfur Removal 508
Compress Supply 510
Compress Storage 512
MeOh Reactor 514
Syngas Storage 516
MeOh Storage 518
Recirc line

FIG. 5

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US 10/37930

A. CLASSIFICATION OF SUBJECT MATTER
IPC(8) - C07C 1/02 (2010.01)
USPC - 585/639; 518/706; 518/702; 700/28; 252/373; 422/18
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC(8) -- C07C 1/02 (2010.01)
USPC -- 585/639; 518/706; 518/702; 700/28; 252/373; 422/18

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
IPC(8) -- B01J; C01B3; C07C; C10G3; C10J3; C25B; F01K;
USPC -- 44/302; 204/274; 205/340; 290/52; 422/186.3

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
PubWest (PGPB,USPT,USOC,EPAB,JPAB); USPTO; Espacenet; Google Patents; Google Scholar; Google -- please see extra sheet

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US 4,766,154 A (Bonnell et al.) 23 August 1988 (23.08.1988) FIGURE; Table I; col 3, ln 60 to col 4, ln 52	1-19
Y	US 4,552,741 A (Melchior) 12 November 1985 (12.11.1985) DRAWING; col 1, ln 22-41; col 2, ln 25-50	1-19
Y	US 2006/0096298 A1 (Barnicki et al.) 11 May 2006 (11.05.2006) para [0002]; [0025]; [0046] to [0048]	1-19
Y	US 5,179,129 A (Studer) 12 January 1993 (12.01.1993) Fig 1; col 3, ln 15-37; col 3, ln 15-37	5
Y	US 4,704,137 A (Richter) 03 November 1987 (03.11.1987) col 1, ln 8-16; col 1, ln 22-41	6,19
Y	US 2008/0057366 A1 (Katikaneni et al.) 06 March 2008 (06.03.2008) para [0070]	4,7
Y	US 4,756,722 A (Knop et al.) 12 July 1988 (12.07.1988) Fig 3; col 7, ln 11-15	10,11,12,14

☒ Further documents are listed in the continuation of Box C. ☐

* Special categories of cited documents:
"A" document defining the general state of the art which is not considered to be of particular relevance
"E" earlier application or patent but published on or after the international filing date
"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
"O" document referring to an oral disclosure, use, exhibition or other means
"P" document published prior to the international filing date but later than the priority date claimed
"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
11 SEPTEMBER 2010 (11.09.2010)	20 SEP 2010
Name and mailing address of the ISA/US Mail Stop PCT, Attn: ISA/US, Commissioner for Patents P.O. Box 1450, Alexandria, Virginia 22313-1450 Facsimile No. 571-273-3201	Authorized officer: Lee W. Young PCT Helpdesk: 571-272-4300 PCT OSP: 571-272-7774

Form PCT/ISA/210 (second sheet) (July 2009)

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US 10/37930

C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US 2008/0302670 A1 (Boyle) 11 December 2008 (11.12.2008) Fig 5; para [0024]; para [0065]; [0071]	3,9,13-19
Y	US 2005/0020700 A1 (Bahnisch) 27 January 2005 (27.01.2005) Fig 1; para [0014]	3
Y	US 6,660,244 B2 (Negishi et al.) 09 December 2003 (09.12.2003) col 16, ln 20-24	4,17
Y	US 4,219,492 A (Konoki et al.) 26 August 1980 (26.08.1980) Drawing; col 5, ln 47-53	9,13-19
Y	US 2008/0223214 A1 (Palamara et al.) 18 September 2008 (18.09.2008) Fig 2; para [0002]; [0004]; [0028]	11
Y	US 1,508,464 A (McFarland) 16 September 1924 (16.09.1924) Fig 1; Fig 2; col 3, ln 20-35	12
A	US 2008/0209891 A1 (Johannes et al.) 04 September 2008 (04.09.2008) para [0028]	1-19

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US 10/37930

Box No. II Observations where certain claims were found unsearchable (Continuation of item 2 of first sheet)

This international search report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claims Nos.:
because they relate to subject matter not required to be searched by this Authority, namely:

2. ☐ Claims Nos.:
because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:

3. ☐ Claims Nos.:
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

Box No. III Observations where unity of invention is lacking (Continuation of item 3 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:
This application contains the following inventions or groups of inventions which are not so linked as to form a single general inventive concept under PCT Rule 13.1. In order for all inventions to be examined, the appropriate additional examination fees must be paid.

Group I: claims 1-19 directed to a fuel synthesis system comprising:
a multiple methanol reactor train, operated in parallel from a supply input of 1) synthesis gas from a solar driven chemical reactor and 2) synthesis gas from a storage unit, or 3) a combination of both, wherein the multiple methanol reactor trains are idled as needed based on a variable amount of synthesis gas fed into the process; and
a controller to control operation of the multiple methanol trains by 1) idling one or more of the methanol reactor trains, 2) altering an output amount being generated by one or more of the methanol reactor trains, 3) switching one or more of the methanol reactor trains to an operational state and 4) any combination of the three, based on an amount of synthesis gas being generated by the solar driven chemical reactor, which is subject to marked variations in volume of synthesis gas output based on seasonal, diurnal and weather effects.

(please see extra sheet)

1. ☐ As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims.

2. ☐ As all searchable claims could be searched without effort justifying additional fees, this Authority did not invite payment of additional fees.

3. ☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos.:

4. ☒ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:

Claims 1-19

Remark on Protest

☐ The additional search fees were accompanied by the applicant's protest and, where applicable, the payment of a protest fee.

☐ The additional search fees were accompanied by the applicant's protest but the applicable protest fee was not paid within the time limit specified in the invitation.

☐ No protest accompanied the payment of additional search fees.

Box No. III continued:

Group II: claim 20 directed to a method for an integrated solar driven chemical plant, comprising:
conducting a chemical reaction in a solar driven chemical reactor having multiple reactor tubes using concentrated solar energy to drive the conversion of the chemical reactant, wherein an endothermic chemical reaction conducted in the reactor tubes includes one or more of the following: biomass gasification, steam methane reforming, methane cracking, using solar thermal energy coming from a concentrated solar energy field;
supplying the products from the chemical reaction for a catalytic conversion of the products from the solar driven chemical reaction into a hydrocarbon fuel or other chemical in a chemical synthesis plant; where an operation of the chemical synthesis plant is dependent upon an amount of product generated in the solar driven chemical reactor; and
a control system for the chemical synthesis plant is configured to send control signals to and receiving feedback from a control system for the chemical reactor, and the control system for the chemical reactor at least indicates the amount of product being generated in the solar driven chemical reactor.

The inventions listed as Groups I-II do not relate to a single general inventive concept under PCT Rule 13.1 because under PCT Rule 13.2 they lack the same or corresponding technical features for the following reasons:

Group II does not include the methanol reactor train and the controller for idling or altering the rector trains of group I.

The common feature of a solar driven chemical reactor in communication with a control system is taught by US 2007/0098602 A1 to Hauter et al. published 3 May 2007 (fig. 2; para [0051]-[0052]); therefore the common feature is not an improvement over the prior art.

None of these technical features are common to the other groups, nor do they correspond to a special technical feature in the other groups. Therefore, unity of invention is lacking.

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Search Terms Used:

ALGORITHM COOLING IDLE IDLING METHANOL MULTIPLE REACTORS PARALLEL PIPELINE PRESSURE REACTOR RECYCL$ REDUCING ATMOSPHERE SOLAR SYNTHESIS STORAGE SYNGAS SYN-GAS SYNTHESIS GAS TEMPERATURE UNDERGROUND

(CATALYST NEAR6 (ACTIVITY OR LIFE))

(HEAT NEAR10 (RECOVER$ OR WASTE OR CAPTUR$ OR EXCHANG$ OR TRANSFER$))

(HOUSING OR ENCLOSURE OR SHELL)

(INTERMITTEN$ OR IRREGULAR INCONSISTEN$ OR UNRELIAB$ OR UNPREDICTAB$) NEAR20 (SOURCE OR SUPPLY)

((METHANOL REACTOR) OR (METHANOL SYNTHESIS REACTOR))

(NIGHT OR OVERCAST OR OVER-CAST OR CLOUD OR CLOUDY OR RAIN OR DAWN OR DUSK)

(PRESSURIZED OR COMPRESSED OR COMPRESSOR)

QUENCH$ NEAR20 (FILTER$ OR FILTRATION OR SCRUBB$ OR CLEANUP OR CLEAN-UP)

(SUN OR SUNSHINE OR SUN-SHINE)