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(54) Title: SYSTEMS AND METHODS FOR SOLAR-THERMAL GASIFICATION OF BIOMASS

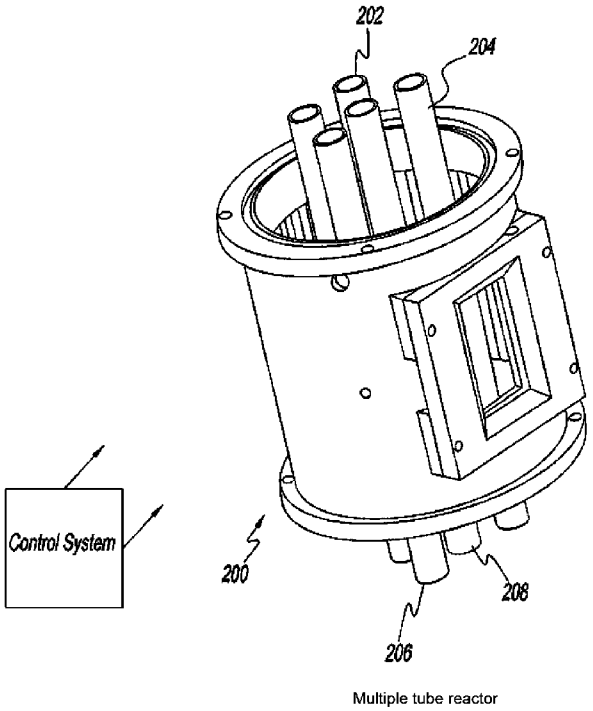


FIG. 2

(57) Abstract: A method, apparatus, and system for a solar-driven chemical plant that may include a solar thermal receiver having a cavity with an inner wall, where the solar thermal receiver is 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. Some embodiments may include a solar-driven chemical reactor having multiple reactor tubes located inside the cavity of solar thermal receiver, wherein a chemical reaction driven by radiant heat occurs in the multiple reactor tubes, and wherein particles of biomass are gasified in the presence of a steam (H2O) carrier gas and methane (CH4) in a simultaneous steam reformation and steam biomass gasification reaction to produce reaction products that include hydrogen and carbon monoxide gas using the solar thermal energy from the absorbed concentrated solar energy in the multiple reactor tubes.

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SYSTEMS AND METHODS FOR SOLAR-THERMAL GASIFICATION OF BIOMASS

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, titled "VARIOUS METHODS AND APPARATUSES FOR SOLAR-THERMAL GASIFICATION OF BIOMASS TO PRODUCE SYNTHESIS GAS" filed June 9, 2009, both of which are hereby incorporated herein by reference in their entireties.

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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 need 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 solar-driven chemical reactor having multiple reactor tubes is located inside the cavity of a solar thermal receiver. A chemical reaction driven by radiant heat occurs in the multiple reactor tubes. Particles of biomass may be gasified in the presence of a steam (H_2O) carrier gas and methane (CH_4) in a simultaneous steam reformation and steam biomass gasification reaction to produce reaction products that include hydrogen and carbon monoxide gas using the solar thermal energy from the absorbed concentrated solar energy in the multiple reactor tubes.

[007] In some embodiments, a solar-driven reactor may be located inside a receiver, which is a cavity that transforms solar

radiant energy into thermal energy. The receiver can include multiple reactor tubes that allow methane or natural gas and steam to pass through a fluidized bed of inert particles to cause a steam methane reaction. When natural gas is passed through a stream methane reaction occurs with a dry reforming of methane with CO2 occurs. Additionally, multiple reactors may be incorporated in the receiver.

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 2 illustrates a diagram of an embodiment of an example multiple tube reactor in accordance with the systems and methods described herein;

figure 3 illustrates a diagram of an embodiment of an example solar tower with receivers and heliostat field in accordance with the systems and methods described herein;

figure 4 illustrates results from simulations of the solar-thermal gasification of biomass with methane;

figure 5 illustrates a diagram of an embodiment of a solar thermal receiver with gasifier tubes in accordance with the systems and methods described herein;

figure 6 illustrates a block diagram of an embodiment of a feed system in accordance with the systems and methods described herein;

figure 7 illustrates a diagram of an embodiment of a solar-driven bio-refinery in accordance with the systems and methods described herein; and

figure 8 illustrates a flow diagram of an embodiment of the systems and methods described herein.

[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] In some embodiments, a solar-driven chemical reactor may have multiple reactor tubes located inside the cavity of a solar

thermal receiver. Within the cavity, a chemical reaction can be driven by radiant heat. The reaction may occur in the multiple reactor tubes. Additionally, particles of biomass can be gasified in the presence of a steam (H2O) carrier gas and methane (CH4) in a simultaneous steam reformation and steam biomass gasification reaction. This can produce reaction products that include hydrogen and carbon monoxide gas using the solar thermal energy from the absorbed concentrated solar energy in the multiple reactor tubes.

[0012] In some embodiments, a solar-driven reactor is located inside a receiver, which is a cavity that transforms solar radiant energy into thermal energy. The receiver can include multiple reactor tubes allowing methane or natural gas and steam to pass through a fluidized bed of inert particles to cause a steam methane reaction. When natural gas is passed through a stream, a methane reaction occurs with a dry reforming of methane with CO2 occurs.

[0013] Figure 1 illustrates a block diagram of an example process flow in accordance with the systems and methods described herein. Some embodiments encompass a solar-driven-biomass gasification to a liquid fuel/electrical process. The process might also include generation, chemical processing, or bio-char, for solar generated syngas derivative products 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.

[0014] 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. The bales are sized to dimensions that may, for example, fit within a

standard box car size or fit within standard compactor size. The entrained-flow biomass feed system can be preceded by a grinding system equipped with mechanical cutting device and a particle classifier, such as a perforated screen or a cyclone, to control the size of the particles that are. The grinding system that has a mechanical cutting device such as a screw and set of filters with micron sized holes/screen diameter sized holes to control particle size. The mechanical screw and set of filters cooperate to grind and pulverize the stock biomass to particles to the micron sized holes of the filters, and the particles of biomass are then fed into and gasified in the solar-driven chemical reactor. 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.

[0015] The biomass may be stored 102. As needed, the biomass might be feed 104 into an example system or apparatus of the instant application. For example, after grinding and pulverizing the biomass to particles, the particles of biomass can be fed into and gasified in the solar-driven chemical reactor. 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.

[0016] 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 syngas.

[0017] Quenching, gas clean up, and ash removal 108 from biomass gasifier 106 may be provided for. Some non-pilot syngas may exit the system 112. Some gasses may be a waste product, while other gasses can be compressed 114 prior to storage 118 or

e.g., methanol synthesis 116. Methanol may then be stored 120 for later methanol to gasoline conversion 122.

[0018] 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 syngas coming out of the quenching and gas clean up portion of the plant and the control system will do so.

[0019] In various embodiments, synthesis gas may be fed to another technical application. Examples include a syngas to other chemical conversion process. The other chemical or chemicals produced can include liquefied fuels such as transportation liquefied fuels. In an example hydrocarbon based fuel, methanol 116 may be formed from syngas. The methanol may be further converted to gasoline or other fuels 122 and various products may be separated out from the gasoline 124 or syngas. These products, e.g., gasoline, may then be stored for later use as an energy source.

[0020] As noted, these biomass feedstock resources can include energy crops such as miscanthus and switchgrass, which are high-impact and high-yield energy crops. A biomass with low lignin content will make it easier to gasify and process in the solar gasifier.

[0021] The stock biomass, such as rice straw, rice hulls, corn stover, high biomass sorghum, switchgrass, miscanthus, bales can be double compressed to facilitate transport via the densification achieved by the double compression allowing very high loadings on the train cars.

[0022] Some embodiments use steam reforming of natural gas, sometimes referred to as steam methane reforming (SMR). SMR is a method to produce hydrogen and carbon monoxide for syngas. At high temperatures (700 – 1500 °C) and in the presence of, for example, a metal-based catalyst (nickel), steam reacts with methane to yield carbon monoxide and hydrogen. In some examples, natural gas may be a mixture of methane and other gases found in deposits under the earth and may contain small amounts of CO2.

Energy + CH_4 + H_2O → CO + 3 H_2

[0023] Additional hydrogen can be recovered by a lower-temperature gas-shift reaction with the carbon monoxide produced. The reaction is summarized by: CO + H_2O → CO_2 + H_2. However, sometimes it is beneficial to eliminate this water gas shift reaction in order to reduce the amount of CO_2 present in the generated synthesis gas. The elimination of the water gas shift reaction may be accomplished by a rapid quenching of the generated products from the reactor at an exit temperature of greater than 900 centigrade to 400 degree or less within 10 seconds.

[0024] In some embodiments, carbon dioxide reforming (also known as dry reforming of methane with CO_2) is a method of producing synthesis gas (mixtures of hydrogen and carbon monoxide) from the reaction of carbon dioxide with hydrocarbons such as methane.

[0025] The methane carbon dioxide reforming reaction may be represented by: $CO_2 + CH_4 \rightarrow 2H_2 + 2CO$

[0026] In some embodiments using biomass gasification, the carbonaceous biomass material particles are fed from the entrained flow biomass feed system. The particles can undergo several distinct chemical processes of the gasification reaction prior to exiting the reactor tubes including the following. For example, initially, pyrolysis of the carbonaceous biomass particles can produce carbonaceous char and volatile components vaporized into gas products.

[0027] In some embodiments, complete gasification of the carbonaceous char including lignin fractions produce gaseous products including carbon monoxide, hydrogen, and tars as well as greater than 99 % pure carbonaceous ash. Additionally, cracking of the tars, including larger hydrocarbons and aromatic compounds collectively known as tars, may occur at greater than 1000 degrees C to produce the substantial tar destruction to less than below 50 mg/m^3 and complete gasification of greater than 90 % of the biomass particles into reaction products including hydrogen and carbon monoxide gas.

[0028] The steps of at least the complete gasification and cracking of tars starts and finishes within the residence time of the biomass particles in the reaction zone in the chemical reactor between the range of 0.01 and 5 seconds. The pyrolysis may start with a low temperature of 300 degree C or less preheating by the carrier gas prior to entering the reactor tubes.

Solar heat + $C_6H_{10}O_5$ (Cellulose) + H_2O (Steam) -> 6CO + $6H_2$

Solar heat + $C_{10}H_{12}O_3$ (Lignin) + $7H_2O$ (Steam) -> 10CO + $13H_2$

[0029] This thermochemical process allows conversion of the entire biomass feedstock (cellulose, hemi-cellulose, and lignin),

thereby reducing the amount of ash present in reaction products and producing a flexible synthesis gas. At least two of the above reactions occur in some embodiments and generally in an embodiment all three reactions occur simultaneously in the reactor tubes.

[0030] Some embodiments may use a fixed bed of carbonaceous fuel (e.g. biomass) through which the gasification agent, e.g., steam, oxygen, air, and/or any combination, flows in a co-current configuration with the fuel downwards. Additionally, a steam blown fluidized bed gasifier may be used to produce a CO2 free gas with a high energy value. Alternatively, small particles of the biomass may be entrained in the gas streams of natural gas and/or gasification agent to mix in the biomass gasification process. Either way, the gasification zone may have steam, biomass, and potentially a methane type reactant which generates biomass gasification reactions as described herein.

[0031] The receiver generally encloses multiple reactor tubes. In an embodiment, the reactor tubes allow methane or natural gas and steam to pass through a heat transfer aid to cause a solar driven steam methane reaction to occur. The heat transfer aid is used to heat the reactant gases. The heat transfer aid may be one or more of the following located inside each reactor tube: a fluidized bed of inert particles, reticulate porous ceramic (RPC) foam, a ceramic monolith, ceramic tubes or aerogels, open structured packed rings such as Raschig rings, or gauze or wire constructed of a high temperature-resistant material. Radiation is the primary mode of heat transfer to the heat transfer aids from the reactor tube walls, and conduction, convection, or some combination of the two are secondary modes of heat transfer.

[0032] Some embodiments may add methane to the biomass. When compared to systems that do not add methane may include the following:
(1) The energy requirement of the solar reactor to produce the equivalent amount of syngas is 33% lower, thus lowering the cost of solar capital components. The energy released in going from 1:1 H2:CO syngas to a H2:CO 2:1 syngas may be contained in the gas stream (as sensible energy). Practically, it can take more solar energy in a pure biomass gasification case to get to the same amount of syngas, but only because you can't practically get the sensible heat back into the feed stream before gasification; and
(2) The above results confirm that various biomass sources ("Kentucky Bluegrass," lignin, corn stover, sorghum) can be gasified at high temperature within seconds using a solar-heated transport tube reactor and that tar formation can be substantially reduced or eliminated.

[0033] Figure 2 illustrates a diagram of an example multiple tube chemical reactor 200 that may be used in a solar driven system. Reactor 200 has multiple reactor tubes 202, 204, 206, 208 and a separate entrainment line may be used for each of the gasifier reactor tubes 202, 204, 206, 208 in the chemical reactor 200. This may allow for independent temperature control and balancing of the amount of particles of biomass flowing in each of the reactor tubes 202, 204, 206, 208 in the multiple tube solar driven chemical reactor 200. The particles of biomass feed can be distributed to the reactor tubes 202, 204, 206, 208 by a lock hopper rotary feed system, such as a Rotofeed® lock hopper rotary feed system. Such a system can allow for balanced feeding to individual reactor tubes 202, 204, 206, 208 and feed rate of the particles is controlled by a weight measuring metering device such as load cells. It may also allow for controlling the rotational rate of the screw or auger that can move

set amounts of biomass along the axis of rotation of the auger. The auger may be located at the base of the lock hopper and can be controlled by a computerized control system such as a Programmable Logic Controller, PC, MAC, CNC, etc, to respond to feed demands of the system. In an embodiment, the computerized control system controls the feed rate of particles of stock biomass in the solar driven chemical reactor based on an amount of solar energy available indicated by sensors including temperature sensors and/or light meters.

[0034] A solar-driven bio-refinery can include a solar driven chemical reactor that has a cyclic operation rather than a continuous steady state operation. Additionally, a computerized control system with sensors may control the feed rate of the biomass material into the multiple reactor tubes with well controlled feed rates that can respond by changing the feed rate of the biomass material based on changing solar availability.

[0035] In some embodiments, a solar-driven chemical reactor can have multiple reactor tubes located inside the cavity of a solar thermal receiver. A chemical reaction can be driven by radiant heat. The reaction can occur in the multiple reactor tubes such that particles of biomass are gasified in the presence of a steam (H2O) carrier gas and methane (CH4). This may occur in a simultaneous steam reformation and steam biomass gasification reaction to produce reaction products that include hydrogen and carbon monoxide gas using the solar thermal energy from the absorbed concentrated solar energy in the multiple reactor tubes.

[0036] In some embodiments, the solar-thermal chemical reactor converts carbonaceous biomass materials into carbon monoxide and hydrogen by reacting the raw particles of biomass material with the steam (biomass gasification) and the steam. For example, this may

occur with the supplemental methane steam reforming at high temperatures, 700-1500 C, with a controlled amount of steam, oxygen, air, and/or any combination, which results in the gas mixture of synthesis gas. Additionally, the steam reacts with both the biomass and the methane, but biomass and methane do not react with each other. A lower amount of steam (H2O) to carbon ratio can be better. In some embodiments, the ratio can be 1:1 to 1:4.

[0037] Additionally, a steam reforming process at a high temperature of 700 – 1500 °C may provide a reaction that avoids a water gas shift reaction that occurs at lower temperatures. This can avoid CO2 creation and still provide a 2:1 H2:CO ratio. For example, a reaction using methane with a steam reforming reaction may allow the reaction in the reactor to generate the correct molar ratio without a water-gas-shift reaction.

[0038] In some embodiments, CO2 may generally be formed in the reaction product gas stream as a result of the water-gas-shift reaction occurring, especially with water feed, and the WGS could be used to achieve a desired molar ratio of H2:CO = 2. However, by material balancing the steam reforming of the natural gas the desired molar ratio of H2:CO = 2 can be achieved without the secondary WGS, which would also generate CO2.

(2) Energy + CO + H2O → CO2 + H2 (water gas shift reaction)

wherein the steam reforming reaction is generating a 3:1 H2:CO ratio and the biomass is generating a 1:1 ratio so less biomass is needed to achieve a 2:1 ratio. In some examples, less energy is needed because all of these reactions are endothermic being driven simultaneously by the concentrated solar energy.

[0039] As illustrated in Figure 2, a control system may be used to balance the biomass gasification reaction, stream reforming reaction,

and dry reforming reaction. For example, balancing gasification with the amount of concentrated solar energy available directed at the solar thermal receiver and solar chemical reactor to keep a temperature at which the chemical reactor operates high enough to maintain the molar ratio of H2 to CO ratio.

[0040] In some embodiments, a control system may be used to keep a reaction temperature high enough for substantially an entire conversion of biomass to product gases and elimination of tar products. For example, the temperature might be at least 1100-1300 degree C. This may provide a reaction that has less than 200 mg/m^3 while keeping the temperature low enough such that the reactor tube wall temperature can be less than 1600 degrees C so that the walls are not structurally weakened. Such temperatures may also significantly reduce receiver efficiency. Additionally, the control system may control the amount of H2O, natural gas, and biomass particles to keep the generated syngas within the desired H2:CO ratio while the chemical reaction can be substantially tar free and have less than 7% by volume CO in the generated syngas. For example, a control system may balance mass in verses available solar energy. This may provide for an endothermic reaction that consumes an amount of available energy and controls concentration and an amount of each reactant product into the chemical reactor to control the molarity and ratio of the reactants going into the reactions in order to control the products coming out of the reactions.

[0041] Some embodiments can include a synthesis reactor that may use the resultant hydrogen molecules and the carbon monoxide molecules (syngas) in the hydrocarbon fuel synthesis process. This can be catalytically reformed using known processes to produce chemicals, including liquid hydrocarbon fuels. For example, fuels such as syngas can be produced and may also be used to drive a gas turbine to produce electricity via an efficient gas turbine or it can

be catalytically reformed to valuable chemicals or liquid fuels. In some embodiments, one or more tubes may be graphite reaction tube with an external SiC coating operating at up to 1500 degree C.

[0042] Figure 3 illustrates a diagram of an example solar tower 300 with receivers 302 and heliostat field 304. In some embodiments solar tower 300 may be used to form a solar-driven bio-refinery with a pneumatic biomass feed system. The feed system can be feedstock flexible via, for example, particle size control of the biomass.

[0043] A chemical reactor 306 receives concentrated solar thermal energy from an array of heliostats 304. The chemical reactor 306 can be, for example, a multiple reactor tube, downdraft, solar driven, chemical reactor, which receives concentrated solar thermal energy from the array of heliostats 304.

[0044] A solar tower 300 may form a portion of a solar-driven bio-refinery that may also include a biomass feed system that has balancing of the feed lines to each of the reactor tubes in a multiple tube chemical reactor. For example, biomass may be fed to the solar reactor in an operation including three parts: biomass transport and preparation for feeding to the solar tower reactor, biomass transport to the top of the, e.g., 500+ foot tower, and distribution into the specific downdraft tubes of the reactor. The distribution may be performed via multiple stages.

[0045] In some embodiments, a solar-driven chemical plant can include a solar thermal receiver having a cavity with an inner wall, where the solar thermal receiver is 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. The solar driven chemical reactor can include a downdraft geometry with the multiple reactor tubes in a vertical orientation and are located inside the solar thermal receiver.

[0046] In some embodiments, the concentrated solar energy may interact with water to convert the water to steam, supply the energy for the reactant gases, and/or interact with other sources to provide heat delivery mechanisms for the heat for the gasification process of the biomass. Additionally, the solar energy may be transferred to the walls of the receiver and walls of the reactor tubes such that the heat is radiantly transferred to the biomass particles. The biomass particles have a lot of surface area to absorb the radiant heat and the particles transfer that heat to the methane molecules.

[0047] Figure 4 illustrate results from simulations of the solar-thermal gasification of biomass with methane. Simulations were carried out for biomass gasification, with and without additive methane, to evaluate the impact of supplemental methane on the solar-thermal process.

[0048] As illustrated in Figure 4 the reactions of an example biomass to syngas may be:

(1) Solar heat + $C_6H_{10}O_5$ (Cellulose) +H_2O (Steam) -> $6CO + 6H_2$

(2) Solar heat + $C_{10}H_{12}O_3$ (Lignin) +$7H_2O$ (Steam) -> $10CO + 13H_2$

(3) Solar heat + CH_4 (Methane) +H_2O (Steam) -> $CO + 3H_2$

Synthesis gas = $nCO + mH_2$, where n and m variable amounts of moles.

[0049] Even if some CO_2 is present in the natural gas consisting mainly of the methane above, the CO_2 and CH_4 react with the high heat via dry reforming to produce hydrogen and carbon monoxide.

(4) $CH_4 + CO_2 \Longrightarrow 2H_2 + 2CO$

[0050] The methane addition in figure 4 eliminates the water gas shift reaction in reactions without methane in order to get to the desired molar $H_2/CO = 2$. Note, when operating the reforming process with concentrated solar radiation, the solar energy is converted into chemical energy and therefore, it increases the energy content of the gas.

[0051] An example biomass to syngas reaction without methane may be:

(1) Solar heat + $C_6H_{10}O_5$ (Cellulose) +H_2O (Steam) -> 6CO + $6H_2$

(2) Solar heat + $C_{10}H_{12}O_3$ (Lignin) +$7H_2O$ (Steam) -> 10CO + $13H_2$

(3) Solar heat + CO+H_2O (Steam) <--> CO_2+H_2

Synthesis gas = $nCO + mH_2$, where n and m variable amounts of moles.

[0052] Figure 5 illustrates a diagram of a solar thermal receiver 500 with gasifier tubes 502. Solar thermal receiver 500 can form a portion of a solar-driven bio-refinery in accordance with the systems and methods described herein. The solar-driven bio-refinery can include a solar driven chemical reactor, a solar thermal receiver such as receiver 500, or both. In some embodiments, solar thermal receiver 500 can be a multiple reaction tube downdraft solar thermal receiver as well as solar driven chemical reactor. Additionally, the feed system may feed biomass particles into the multiple reaction tubes 502, in which the particles of biomass may be gasified in the presence of steam at a temperature exceeding 950 degrees C from an exit of a gasification reaction zone of the reactor tubes.

[0053] In some embodiments, a solar-driven chemical plant may use methane from natural gas. Additionally, the biomass and natural gas may be co-fed with steam heated by the solar energy to dry reform heated CO2 with CH4 the methane with the CO2 into syngas, such that, even if some CO2 is present in the natural gas consisting mainly of methane, the CO2 and CH4 react with the high heat via dry reforming to produce hydrogen and carbon monoxide substantially free of CO2.

[0054] For example, the reaction may include:

Energy from H2O + CH4 + CO2 ==> 2H2 + 2CO +H2O.

[0055] In some cases, small amounts of CO2 in the natural gas can react with methane to produce additional synthesis gas. Additionally, thermodynamics indicate that a CO2-free syngas can be produced when biomass and methane are co-fed with steam at 1200 degree C in stoichiometric proportions to produce a molar ratio of H2:CO = 2 (two moles of hydrogen gas - carbon monoxide per liter). The majority of the reduction of carbon dioxide present in the generated syngas from the reactor comes from that concentrated solar energy, which can externally drive the steam reforming of the methane and biomass gasification of the carbon in the biomass reactions. Additional CO2 reduction may occur by rapid quenching of the reactor products to avoid the water gas shift reaction and a dry reforming of methane reaction simultaneous with the steam reforming to consume CO2 present and/or generated during the reactions in the reactor tubes. Also the 2:1 H2:CO molar ratio can be in a range from 2.0 to 2.8.

[0056] In some examples, when natural gas is used, it is possible for the plant to produce 5 to 10% of the syngas on demand via oxidation of NG using high temperature oxidizers (O2, not air) that essentially fits into a tee (T) just before the downstream syngas

catalytic reforming synthesis. Thus, in a partial oxidation system, the system can have a catalytic oxidizer. A reaction that may take place is: $CH_4+0.5O_2=CO+2H_2$ (partial oxidation reforming). Additionally, this supplemental source may be used to raise the amount of H_2 present in H_2:CO syngas. This process may be run in parallel with the main solar driven reactor.

[0057] In some examples, the co-feeding of methane, potentially in natural gas, with water and biomass, produces a CO_2-free synthesis gas. In such an example CO_2 levels may be less than 7% (by volume) of the syngas stream and have a desirable molar ratio of H_2:CO = 2. Such a reaction may also avoid a water-gas-shift reaction that may otherwise produce CO_2. Tar formation may also be avoided at an approximately 1100-1300 degree C operating temperature. In some examples, use of biomass carbon can produce CO_2-free syngas. Substantially 100% of the biomass carbon may produce the useful CO component of syngas. Additionally, with CO_2 levels at less than 7% (by volume) of the syngas stream, a downstream amine train to remove CO_2 prior to catalytic reforming of the syngas might no longer be necessary. Operation in temperature regimes where tar may be eliminated and reaction can be extremely fast due to radiation heat transfer may be used.

[0058] In some embodiments, co-feeding of methane (CH_4) with the biomass may be used such that particles of biomass facilitate the radiation heat transfer. This can raise the temperature in the tubes to a level to reform the methane and cause the biomass gasification reaction. In other systems, separate streams mighty be required and a separate solid particle addition might be needed to accomplish this such that the conversion of methane is combined with biomass gasification using steam heated by the solar energy to generate the synthesis gas.

[0059] In some embodiments, a solar-driven reactor may be located inside a receiver. A receiver is a cavity that transforms solar radiant energy into thermal energy. The receiver can comprise multiple reactor tubes. The reactor tubes may allow methane or natural gas and steam to pass through a fluidized bed of inert particles to cause a steam methane reaction. Natural gas can be passed through a stream such that a methane reaction occurs with a dry reforming of methane with CO2 occurs. Additionally, multiple reactors can be incorporated in a receiver. To increase the size of a plant, more receivers may be added. Each reactor may be a downdraft tube.

[0060] Figure 6 illustrates a block diagram of a feed system 600. The grinding system 603 has a mechanical cutting device used to grind the biomass into primary particles, which are to be fed into the solar driven chemical reactor. The grinding system supplies primary particles that have an average smallest dimension size between 200 microns (um) and 2000 um, with a general range of between 500 um and 1000 um to a lock hopper system 604 with a standard belt conveyer. The biomass particles are then fed across a pressure boundary into a pressurized entrainment gas for feeding into in the solar driven chemical reactor. The feeding vessel may use an Auger/Screw feeder or an airlock-type rotational solids feeding/rate metering device.

[0061] The entrainment-flow biomass feed system 600 can include a pressurized lock hopper 604 that feeds the biomass to a rotating screw conveyor 602 and a metering device and then into an entrainment gas pipe at the lock hopper exit 606. A flow splitter distributes the particles of biomass into multiple entrainment gas lines to feed at least two or more of the multiple reactor tubes making up the solar driven chemical reactor. The entrainment gas for the pneumatic biomass feed system may be a pressurized dry steam

generated from waste heat recovered from either 1) the methanol/Methanol-To-Gasoline (MTG) units in the hydrocarbon fuel synthesis process or 2) the products from the gasification reaction in the solar driven chemical reactor. The entrainment gas may also be CO2, natural gas, an inert gas, steam generated in any fashion, or other similar entrainment gas.

[0062] Additionally, an entrained-flow biomass feed system having one or more feed lines to feed the biomass particles into the multiple reactor tubes, in which a separate entrainment line and metering device of the entrained-flow biomass feed system is used for each of the gasifier reactor tubes in the chemical reactor. This may allow for balancing of 1) amount of particles of biomass flowing through the feed line to each reactor tube to 2) an amount of solar energy available for that reactor tube in the multiple tube solar driven chemical reactor. Feed rate of the biomass particles can be controlled by a metering device and controlling a rotational rate of a screw 602 at a base of the lock hopper 604, which responds to a feed demand signal received from the control system.

[0063] Thus, control of the rotational rate of the screw or auger 602 can move set amounts of biomass along the axis of rotation of the auger 602. The auger 602 may be located at the base of the lock hopper 604 and can be controlled by a control system to respond to feed demand of the system. As discussed, the control system controls the feed rate of particles of biomass in the solar driven chemical reactor based on an amount of solar energy available indicated by sensors including temperature sensors and/or light meters.

[0064] In some embodiments, additional biomass may be used in a biomass methane gasification reformation as compared to biomass gasification. For example, in some embodiments (about 2.5X) to produce a given mass of the required H2/CO = 2 molar ratio. In this

example embodiment, the reaction is substituting carbon in the natural gas for carbon sourced from the biomass carbon. In addition, there may be excess water in the reactor for the straight biomass gasification route. Hence, reactor materials may be oxidation resistant and steam resistant.

[0065] Some embodiments include an entraining gas biomass feed system that uses an entrainment carrier gas comprising natural gas, steam, oxygen, air, and/or any combination of these and supplies a variety of feed stock biomass sources fed as particles into the solar driven chemical reactor. The entrainment carrier gas can be natural gas, steam, or any combination of natural gas and steam. Additionally, the entraining gas biomass feed system may receive ground and pulverized biomass with a particle size that is between 150 and 300 microns. The particle size has 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. Similar particle size, and use of the multiple tube design with the external concentrated solar thermal energy driving the biomass gasification reaction, steam reforming reaction, and dry reforming reaction may be used to allow the process to be feedstock flexible, with no major equipment redesign required to change feedstocks.

[0066] In some embodiments, two or more types of biomass may be fed. These biomasses may be fed individually or in combinational mixtures, from the group consisting of cellulose, lignin, pine sawdust, rice straw, corn stover, switch grass, energy crops, source separated green wastes, sorghum, Algae, and other similar biomass sources. This may be done as long as a few parameters are controlled, such as particle size of the stock biomass and operating temperature range of the reactor tubes.

[0067] Figure 7 illustrates a diagram of a solar-driven bio-refinery 700 in accordance with the systems and methods described herein. An array of heliostats 702 can be used to focus light onto a window 704 of a reactor 706. In reactor 706 biomass particles can be reduced to syngas, which in turn can be synthesized into liquid fuel in liquid fuel synthesizer 708.

[0068] For example, in some embodiments, an on-site fuel synthesis reactor 708 may receive the hydrogen and carbon monoxide products from the gasification reaction and use the hydrogen and carbon monoxide products in a hydrocarbon fuel synthesis process to create a liquid hydrocarbon fuel. The fuel synthesis reactor 706 may be geographically located on the same site as the chemical reactor and integrated into the process to utilize the hydrogen and carbon monoxide products from the gasification reaction.

[0069] In some embodiments, the addition of methane (CH4 i.e. primary constituent in natural gas) can be used at the solar-thermal operating temperatures to stretch the use of biomass carbon to produce essentially CO2-free sygnas (at less than CO2 levels at less than 7% (by volume) of the syngas stream) via dry reforming of methane with the carbon dioxide. The biomass and the supplemental natural gas are rapidly gasified and reformed with steam, and all are heated by the solar energy concentrated into the solar-thermal gasifier, which primarily uses radiant heat to drive the chemical reaction.

[0070] In some embodiments, an on-site chemical plant 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 may be used. The on-site chemical plant can have 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, or other chemical product.

[0071] Additionally, down stream of the reactor, one or more knock out drums may exist to remove excess water from the generated syngas. For biomass/methane, less than an amount of 2-5% of CO2 is formed.

[0072] Figure 8 illustrates a flow diagram in accordance with the systems and methods described herein. In step 800, biomass grinding can occur. Equipment generally used for grinding biomass includes impact mills (e.g. hammer mills), attrition mills, and kinetic disintegration mills (e.g. flail mills). A hammer mill system can be used to grind the bales (loaded by conveyer) into primary particles, which are to be fed into the solar thermal gasifier. The re-ground particles have an average size between 500 um and 1000 um, and are loaded into the lock hopper system with a standard belt conveyer.

[0073] In step 802 biomass feeding occurs. In some embodiments, high pressure feeding may be used. High pressure feeding of solids of biomass with gasification at pressure may reduce capital cost due to the ability to use smaller compressors in some such systems. Additionally, operating cost may be reduced because energy for pressurizing carrier gas comes from the sun, as opposed to from electricity. The lock hopper system can feed the reactor processes at pressure. For example, the feeding system can entrain the biomass materials in steam at high pressure, successfully disengage the particulates in the cyclone system, and distribute flow appropriately to the reactor tubes.

[0074] In step 804, gasification occurs. For example, in some embodiments, concentrated solar thermal energy drives gasification

of the particles of the stock biomass to generate at least hydrogen and carbon monoxide products from the gasification reaction.

[0075] In step 806 fuel synthesis occurs. An on-site fuel synthesis reactor can receive the hydrogen and carbon monoxide products from the gasification reaction and use the hydrogen and carbon monoxide products in a hydrocarbon fuel synthesis process to create a liquid hydrocarbon fuel. The fuel synthesis reactor may be geographically located on the same site as the chemical reactor and integrated into the process to utilize the hydrogen and carbon monoxide products from the gasification reaction.

CLAIMS

What is claimed is:

We claim:

1. A solar-driven chemical plant, comprising:

a solar thermal receiver having a cavity with an inner wall, where the solar thermal receiver is aligned to absorb concentrated solar energy from one or more of 1) an array of heliostats, 2) a solar concentrating dish, and 3) any combination of the two; and

a solar-driven chemical reactor having multiple reactor tubes located inside the cavity of solar thermal receiver, wherein a chemical reaction driven by radiant heat occurs in the multiple reactor tubes, and wherein particles of biomass are gasified in the presence of a steam (H2O) carrier gas and methane (CH4) in a simultaneous steam reformation and steam biomass gasification reaction to produce reaction products that include hydrogen and carbon monoxide gas using the solar thermal energy from the absorbed concentrated solar energy in the multiple reactor tubes.

2. The solar-driven chemical plant of claim 1, wherein the solar driven chemical reactor has a downdraft geometry with the multiple reactor tubes in a vertical orientation that are located inside the solar thermal receiver and wherein the solar-thermal chemical reactor converts carbonaceous biomass materials into carbon monoxide and hydrogen by reacting the raw particles of biomass material with the steam biomass gasification and the steam with the supplemental methane steam reforming at high temperatures, 700-1500 C, with a controlled amount of steam, natural gas, and any combination, which then results in the gas mixture of synthesis gas.

3. The solar-driven chemical plant of claim 1, wherein the steam reacts with both the biomass and the methane, but biomass and methane does not react with each other, and wherein a steam (H2O)

to carbon molar ratio is in the range of 1:1 to 1:4 and wherein multiple reactors are incorporated in a receiver.

4. The solar-driven chemical plant of claim 1,

wherein the methane comes from natural gas, and the biomass and natural gas are co-fed with steam heated by the solar energy to dry reform the methane with CO2 either contained within the natural gas or fed as a separate feedstock, such that, even if some CO2 is present in the natural gas consisting mainly of methane, the CO2 and CH4 react with the high heat via dry reforming to produce hydrogen and carbon monoxide, and

wherein a synthesis gas having less than 7 % of CO2 by volume syngas is produced when biomass and methane are co-fed with steam at temperature ranges of 750-1300 degrees C in the stoichiometric proportions to produce a molar ratio of H2:CO in a range from 1.0 to 3.0.

5. The solar-driven chemical plant of claim 1, further comprising:

a steam reforming process at a high temperature of 700 – 1500 ℃ such that the reaction avoids a water gas shift reaction that is equilibrium favored at lower temperatures and thus avoids extra CO2 creation from the water gas shift reaction, the reaction using methane with a steam reforming reaction to allow the reaction in the reactor to generate the desired molar ratio for liquid fuels or chemical synthesis without a water-gas-shift reaction.

6. The solar-driven chemical plant of claim 1,

wherein the co-feeding of methane in natural gas with water and biomass produces a low CO2 synthesis gas with CO2 levels at less than 7% by volume in the syngas stream and having a molar ratio of H2:CO = 2.0-3.0 as well as avoids a water-gas-shift reaction that may otherwise produce CO2, and

wherein tar formation is mitigated at an approximately 1100-1300 degree C operating temperature, and a synthesis gas having less than 200 mg/m^3 of tar for hydrocarbons with molecular weights between 30 and 1000 is generated.

7. The solar-driven chemical plant of claim 1,

wherein the reactor tube materials are oxidation resistant and steam resistant; and

wherein the steam reforming reaction is generating a 3:1 H2:CO ratio and the biomass is generating a 1:1 H2:CO ratio, so less biomass is needed to achieve a syngas product with an approximate 2.1-2.8:1 H2:CO ratio that is appropriate for liquid fuels and chemical synthesis than if the biomass was gasified without the methane present.

8. The solar-driven chemical plant of claim 1, further comprising:

wherein in the reactor tube the co-feeding of methane (CH4) with the biomass occurs such that the particles of biomass facilitate the radiation heat transfer to raise temperature in the tubes to a level to reform the methane and cause the biomass gasification reaction such that the steam reforming of methane and dry reforming of methane is combined with biomass gasification using steam heated by the solar energy to generate the synthesis gas; and

wherein the concentrated solar energy is transferred to the walls of the receiver and wall of the reactor tubes such that the heat is radiantly transferred to the biomass particles, the biomass particles have a lot of surface area to absorb the radiant heat, and then the particles of biomass transfer that heat effectively to the methane and steam molecules.

9. The solar-driven chemical plant of claim 1, further comprising:

an entraining gas biomass feed system that uses an entrainment carrier gas comprising natural gas, steam, air, and/or any combination of these and supplies a variety of feed stock biomass sources fed as particles into the solar driven chemical reactor;

wherein the entrainment carrier gas is natural gas, steam, or any combination of natural gas and steam;

wherein the particle size distribution of the biomass feedstock has an average smallest dimension size between 200 microns um and 2000 um in diameter, with a general range of between 500 um and 1000 um; and use the simple multiple tube design with the external concentrated solar thermal energy driving the biomass gasification reaction, steam reforming reaction, and dry reforming reaction to allow the process to be feedstock flexible, with no major equipment redesign required to change feedstocks; and

where the variety includes two or more types of biomass that can be fed, individually or in combinational mixtures, from the group consisting of cellulose, lignin, pine sawdust, rice straw, corn stover, switch grass, energy crops, source separated green wastes, forestry wastes, forestry thinnings, sorghum, and Algae, by controlling particle size of the stock biomass and operating temperature range of the reactor tubes.

10. The solar-driven chemical plant of claim 1, further comprising:

A control system configured to control the receiver temperature by balancing the biomass and natural gas or methane feed rate against available solar energy such that the temperature in the receiver is maintained at a desired setpoint in the range of 800°-1600° C by the balance of solar energy entering the aperture, energy consumed by the chemical reaction and reactant/product sensible heat, and thermal losses from the receiver by radiation, convection and/or conduction; and

wherein the control system 1) keeps a temperature at a high enough temperature (1000°-1300° C) for a substantially entire conversion of the biomass to product gases and elimination of tar products to a concentration of less than 200 mg/m^3 and 2) keep a temperature low enough (<1600° C) for the reactor tube wall to not structurally weaken or significantly reduce receiver efficiency, and control amount of H2O, Natural gas, and biomass particles to keep the generated syngas within the desired H2:CO ratio and to maintain less than 7% by volume CO2 in the generated syngas.

11. The solar-driven chemical plant of claim 1, further comprising:

a synthesis reactor having a supply input to receive syngas containing the resultant hydrogen molecules and the carbon monoxide molecules from the solar driven chemical reactor, where the synthesis reactor uses the syngas in the hydrocarbon fuel synthesis process which are catalytically reformed to produce chemicals.

12. A solar-driven reactor located inside a receiver, comprising:

a cavity that transforms solar radiant energy into thermal energy, the receiver encloses multiple reactor tubes of the solar driven reactor, the reactor tubes are configured for 1) methane 2) natural gas, 3) steam and 4) a combination of the three to pass through a heat transfer aid to cause a steam methane reaction using the thermal energy from the solar radiant energy;

wherein a heat transfer aid is used to heat the reactant gases, where the heat transfer aid is one or more of the following located inside each reactor tube: a fluidized bed of inert particles, reticulate porous ceramic (RPC) foam, a ceramic monolith, ceramic tubes or aerogels, open structured packed rings including Raschig rings, gauze or wire constructed of a high temperature-resistant material, and any combination of these; and

wherein radiation is the primary mode of heat transfer to the heat transfer aids from the reactor tube walls, and conduction, convection, or some combination of the two are secondary modes of heat transfer.

13. The solar-driven chemical plant of claim 12 further comprising:

a moving bed of carbonaceous feedstock through which the gasification agent flows in a co-current or counter-current configuration to achieve gasification and the bed is heated with solar thermal energy.

14. The solar-driven chemical plant of claim 12, further comprising:

a first tube that is graphite reaction tube with an external SiC coating operating at up to 1500 degree C and wherein methane is added to the biomass such that the energy requirement of the solar reactor to produce the equivalent amount of sygnas is lower and wherein biomass sources can be gasified at high temperature using a solar-heated transport tube reactor and such that tar formation can be substantially reduced to less than 200 mg/m^3.

15. The solar-driven chemical plant of claim 12, wherein, when natural gas is used, the plant produces 5 to 10% of high H2 syngas (>2:1 H2:CO ratio) on demand via oxidation of natural gas using high temperature oxidizers that is combined with the syngas from solar biomass gasification just before the downstream syngas catalytic reforming synthesis such that the high H2 syngas is used to raise the amount of H2 present in the combined syngas to the desired H2:CO ratio and syngas is available on demand when solar flux is low.

16. A method of producing chemicals using solar energy comprising:

providing a solar-driven chemical plant, including:

a solar thermal receiver having a cavity with an inner wall, where the solar thermal receiver is 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;

a solar-driven chemical reactor having multiple reactor tubes located inside the cavity of solar thermal receiver, wherein a chemical reaction driven by radiant heat occurs in the multiple reactor tubes, and wherein particles of biomass are gasified in the presence of a steam (H_2O) carrier gas and methane (CH_4) for a simultaneous biomass gasification reaction and steam methane reforming reaction; and

providing a biomass source comprising at least one of cellulose, lignin, pine sawdust, rice straw, corn stover, switch grass, energy crops, source separated green wastes, sorghum, forestry thinnings forestry waste, and algae to the reactor tubes; and

causing the simultaneous steam methane reformation and biomass gasification reaction to produce reaction products that include hydrogen and carbon monoxide gas using the solar thermal energy from the absorbed concentrated solar energy in the multiple reactor tubes.

17. The method of claim 16, wherein the solar-thermal chemical reactor converts carbonaceous biomass materials into carbon monoxide and hydrogen by reacting the raw particles of biomass material with the steam (biomass gasification) and the steam with the supplemental methane at high temperatures, 700-1500° C, with a controlled amount of steam, and methane, and any combination, which results in the gas mixture of synthesis gas.

18. The method of claim 16, further comprises

providing the methane from natural gas;

co-feeding the biomass and the natural gas with steam heated by the solar energy to dry reform the methane with CO2 either contained within the natural gas or fed as a separate feedstock, such that, even if some CO2 is present in the natural gas consisting mainly of methane, the CO2 and CH4 react with the high heat via dry reforming to produce hydrogen and carbon monoxide; and

wherein a synthesis gas having less than 7 % of CO2 by volume syngas is produced when biomass and methane are co-fed with steam at temperature ranges of 750-1300 degrees C in the stoichiometric proportions to produce a molar ratio of H2:CO in a range from 1.0 to 3.0.

19. The method of claim 16,

wherein a co-feeding of methane in natural gas with water and biomass produces a low CO2 synthesis gas with CO2 levels at less than 7% by volume in the syngas stream and having a molar ratio of H2:CO = 2.0-3.0 as well as avoids a water-gas-shift reaction that may otherwise produce CO2; and

wherein tar formation is mitigated to less than 200 mg/m^3 at an approximately 1100-1300 degree C operating temperature, where substantially 100% of the biomass carbon produces the useful CO component of syngas.

20. The method of claim 16, further comprising:

an on-site chemical plant that is geographically located on the same site as the chemical reactor and integrated to receive syngas containing the hydrogen and carbon monoxide products from the simultaneous biomass gasification reaction and steam methane reforming reaction, wherein the on-site chemical plant has an input to receive syngas containing the hydrogen and carbon monoxide products and use them in a hydrocarbon fuel synthesis process to create a liquid hydrocarbon chemical product.

AMENDED CLAIMS
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1. An apparatus, comprising:

a chemical reactor that has multiple reactor tubes located inside the cavity of a thermal receiver, where in the multiple reactor tubes a chemical reaction driven by radiant heat occurs, wherein the chemical reaction includes one or more of biomass gasification, steam methane reforming, methane cracking, steam methane cracking to produce ethylene, metals refining, and CO2 or H2O splitting to be conducted in this chemical reactor using the radiant heat;

an indirect radiation driven geometry in the form of the cavity wall of the thermal receiver integrates and locates the chemical reactor inside the receiver, where the inner wall of the receiver cavity and the reactor tubes exchange energy primarily by radiation creating an oven effect, allowing for the reactor tubes to achieve a fairly uniform temperature profile; and

an exit of a gasification zone in the multiple reactor tubes, wherein reaction products have a temperature from the exit of the gasification zone that equals or exceeds 900 degrees C.

2. The chemical plant of claim 1, further comprising:

wherein the thermal receiver is 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, where the solar thermal receiver has cavity walls;

wherein the radiant heat driven chemical reactor is driven by the concentrated solar energy and thus is a solar-driven chemical reactor that has multiple reactor tubes;

an aperture 1) open to an atmosphere of the Earth or 2) covered by a window, to pass the concentrated solar energy into the solar thermal receiver to impinge on the multiple reactor tubes and inner cavity wall of the receiver;

an outer shell of the solar thermal receiver, wherein the one or more apertures are part of the outer shell of the solar thermal receiver;

wherein the chemical reaction is the biomass gasification, where particles of biomass are gasified in the presence of a carrier gas in an endothermic gasification reaction inside the multiple reactor tubes to produce hydrogen and carbon monoxide products;

the multiple reactor tubes in this solar-driven chemical reactor design increase available reactor surface area for radiative exchange to the biomass particles, as well as inter-tube radiation exchange resulting in even distribution of solar energy;

wherein the reactor tubes serve the dual functions of 1) segregating the biomass gasification reaction environment from the atmosphere of the Earth and 2) transferring energy by solar radiation absorption and heat radiation, convection, and conduction to the reacting particles of biomass to drive the endothermic gasification reaction of the particles of biomass flowing through the reactor tubes, and wherein high heat transfer rates of the reactor tubes and cavity walls allow the particles of biomass to achieve a high enough temperature necessary for substantial tar destruction and gasification of greater than 90 percent of the biomass particles into reaction products including the hydrogen and carbon monoxide gas in a very short residence time between a range of 0.01 and 5 seconds; and

wherein the inner wall of the receiver absorbs or highly reflects the concentrated solar energy from the array of heliostats to cause energy transport by thermal radiation or reflection to generally convey that heat to the biomass particles via the walls of the solar-driven chemical reactors.

3. The chemical plant of claim 2, further comprising:

a material making up the inner wall of the receiver cavity has mechanical and chemical properties to retain its structural strength at high temperatures between 1100-1500 °C, have very high emissivity of $\varepsilon>0.8$ or high reflectivity of $\varepsilon<0.2$, as well as high heat capacity (>200 J/kg-K) and low thermal conductivity (<1 W/m-K) for the receiver cavity; and

a material making up the reactor tubes possesses high emissivity ($\varepsilon>0.8$), high thermal conductivity (>1 W/m-K), moderate to high heat capacity (>150 J/kg-K), wherein

the one or more apertures are part of an outer shell of the receiver and the material making up the reactor tubes is also resistant to the oxidizing air environment in the cavity and the reducing environment of the biomass gasification reaction.

4. The chemical plant of claim 2, further comprising:

one or more feed lines to add inert solid particles entrained with biomass particles or reactant gases into the reactor tubes, wherein the indirect radiation driven geometry of the solar thermal receiver is configured as an indirect gasifier with a primary mode of heat transfer of radiation to the biomass particles and the inert solid particles entrained with biomass particles,

wherein the inner wall of the cavity acts as a radiation distributor by either absorbing solar radiation an re-radiating to the reactor tubes or reflecting the incident radiation to the tubes, where the radiation is absorbed by the reactor tubes, and the heat is transferred, by conduction to the inner wall of the reactor tubes, where it radiates to the reacting particles at temperatures between 900° C and 1400° C,

wherein the inner wall of the receiver cavity is made of the absorbing solar energy material rather than the highly reflective material, and

wherein the rapid gasification of dispersed falling biomass particulates with a resultant stable ash formation, complete amelioration of tar to less than 500 milligrams per normal cubic meter, and the production of the hydrogen and carbon monoxide products occurs.

5. The chemical plant of claim 2, further comprising:

one or more additional fixed radiant heat structures located within the cavity to store additional heat energy, wherein an amount of stored heat in the mass of the walls of the receiver, tube walls and additional fixed radiant heat structures is set for a transfer of heat radiation from walls of the receiver, tube walls, as well as the one or more additional fixed radiant heat structures to transfer enough heat to the particles of the biomass in the aerosol stream to gasify and convert the biomass reactant into the greater than 90 percent gasification of the biomass particles into the reactant products during intermittent periods of the day when the Sun is partially or completely blocked by clouds.

6. The chemical plant of claim 2, further comprising:

an amount of concentrated solar energy from the heliostat field equal to or greater than 2 MW per meters squared of solar energy at the apertures, which gives the receiver cavity to have a capacity of at least 2000 kW and generally around 80,000 kW, wherein the multiple tube construction of the cavity increases the surface area for radiative transfer to the biomass particles over a simple reaction tube, and a shape of the reactor tubes is substantially rectangular, which also yields a higher surface area for equivalent volume than cylindrical shaped tubes.

7. The solar-driven chemical plant of claim 2, further comprising:

a downdraft geometry to the multiple reactor tubes in which the biomass particles fall through the downdraft reactor design, where the downdraft permits disengagement of volatile alkali and tar components prior to cooling and remediation on the non-volatile

ash, wherein the reactor tube walls are at a temperature of greater than the 900 degrees C with high heat transfer rates that allow the biomass particles to achieve the high temperatures necessary for tar destruction and complete gasification in the very short residence times of 0.01 seconds to 5 seconds.

8. The solar-driven chemical plant of claim 2, further comprising:

two or more feed lines to the multiple reactor tubes, where each feed line supplies a reactor tube, and controls a dispersion pattern of the biomass particles into its corresponding reactor tube to maximize radiation absorption by the particles when injected into the reactor tube based on a shape and width of the outlet of the feed line pipe carrying the biomass particles to its corresponding reactor tube; and

the two or more feed lines supply the particles of biomass having an average smallest dimension size between 50 microns (um) and 2000 um, and the small particle size and large surface area of the dispersed particles ensures there is a low temperature gradient within the particles, high mass transfer between the particles surface with water vapor in the entrainment gas, and efficient heat transfer to the reactant gases from the particles, facilitating gasification of biomass particles in the short residence times of 0.01 second to 5 seconds.

9. The chemical plant of claim 2, further comprising:

an insulation layer around the cavity of the solar thermal receiver; wherein the receiver is configured with only one or more apertures and no windows, where the multiple reactor tubes are located in the center of the cavity;

a thickness of the insulation layer is set to control conductive heat losses from the cavity, and the heliostats are aligned with the one or more apertures in the cavity and the apertures are sized to have a high average concentration of solar energy greater than 1000 suns at the one or more apertures, and where a shape of the cavity is designed so an average temperature in the cavity and the average concentration of solar energy at the one or more apertures control radiative losses from the cavity;

a design and orientation of the aperture, and cavity working fluid (buoyancy) are set to control convective losses, wherein the inner cavity wall at least partially encloses the multiple reactor tubes to act like an oven, spreading heat flux around through radiation and giving a much more even flux profile on the reactor tubes, both azimuthally and axially, than the incident solar radiation by itself has, wherein an averaging effect on the heat flux radiated from the absorbing cavity walls and multiple tubes occurs within the cavity; and

a heliostat field that focuses the moving Sun to shift the average concentrated solar energy weighting from West to East across the aperture and impinging on the axis of the reactor tubes themselves through the course of each day, and wherein 1) the oven effect of the cavity along with 2) the particles of biomass, which tend to average energy amongst themselves at their design volumetric loadings, combine to give the fairly uniform temperature profile and subsequent fairly uniform radial reaction profile of the biomass particles.

10. The chemical plant of claim 2, further comprising:

a length and diameter dimensions of the gasification reaction zone of each of the reactor tubes, along with an arrangement and an amount of the tubes are matched to the incident solar flux to allow high heat transfer and to give the fast reaction time of 0.01 second to 5 seconds at the gasification temperatures,

wherein the inside walls of the receiver cavity are constructed of a high temperature-resistant refractory material including one or more of: SiC, alumina plate, alumina/SiO2 fiber, and

wherein a first of the multiple tubes has a different diameter than a second of the multiple tubes, and where a shape of each tube is a cylindrical shaped pipe.

11. The chemical plant of claim 2, further comprising:

one or more apertures and no windows in a shell of the cavity; where the gasification reaction zone in the multiple tubes has an inner atmosphere of the tubes, which is sealed from the environment present in the cavity; and

a substantial axial length of the reactor tube, where the biomass particles are passed through the reaction zone of the reactor tube along a predetermined path which is substantially coincident with the reactor tube axis, and the biomass particle reactants are confined entirely within the reactor tube, wherein an arrangement of the cavity causes high flux (100-300 kW/m^2) radiant energy from the walls and tubes to be directed through the reactor tubes to coincide with the reaction zone of each reactor tube.

12. The chemical plant of claim 2, further comprising:

a thick layer of insulation around a solar thermal receiver containing the chemical reactor is set to limit heat losses by conduction from a cavity of the receiver in conjunction with a moveable insulative door that covers a receiver aperture to limit heat losses by radiation, conduction, and convection from leaving the cavity during periods of non-operation, including inclement weather or nighttime, so that the temperature in the cavity is decreased by less than 400 °C in a 12 hour period when no concentrated solar energy is directed at the cavity aperture, where the insulation and door maintain heat energy to reduce both 1) the amount of time required to heat the receiver and reactor tubes following a down period and 2) the thermal shock and stresses imparted to the receiver and reactor materials of construction.

13. The chemical plant of claim 2, further comprising:

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, wherein the on-site fuel synthesis reactor has an input to receive the hydrogen and carbon monoxide products in a hydrocarbon fuel synthesis process performed in the on-site fuel synthesis reactor to create liquid hydrocarbon fuels or chemicals, wherein the liquid hydrocarbon produced from the on-site fuel synthesis reactor is one or more of jet fuel, dimethyl ether (DME), gasoline, diesel, mixed alcohol, methanol, synthetic natural gas in liquid form, hydrocarbon chemicals, and heating oil, where the on-site fuel synthesis reactor being integrated with the solar driven chemical reactor allows a fraction of the concentrated solar energy from

the array of heliostats to be stored as an easily transportable and stable chemical energy source in the liquid hydrocarbon fuel form.

14. The chemical plant of claim 2, where a material and an indirect, solar heated gasification design of the multiple reactor tubes allows for feedstock flexibility in the type of biomass making up the particles of biomass, and obviates any need for an exothermic/endothermic reaction balancing in the chemical reactor design because the concentrated solar energy drives the endothermic gasification reaction and a radiation-based heat transfer balancing makes the endothermic reaction gasification quite forgiving in terms of internal reaction balance, and thus, at least two or more different types of biomass materials can be used in the same multiple reactor tube geometry of the chemical reactor, obviating any need for a complete reengineering when a new type of biomass feedstock is used.

15. The chemical plant of claim 1, further comprising:

one or more feed lines to add inert heat absorbing particles, including silica, Carbo HSP, or other proppants, entrained along with the biomass particles, and where heat energy to drive the gasification reaction of the biomass particles or partially reacted gas comes from the following three sources 1) the heat absorbing particles, 2) the reactor tubes, and 3) an inner wall of the cavity;

an ash and particle storage mechanism configured to accumulate the inert heat absorbing particles and ash remnants of the biomass from the gasification reaction that exit the chemical reactor; and

a separator configured to separate the inert heat absorbing particles and ash remnants from the gas products into the ash and particle storage mechanism, which stores these particles and ash remnants to extract their heat in order to heat a working fluid that drives an electricity generation apparatus or other apparatus used in doing heat based processes.

16. The chemical plant of claim 2, further comprising:

one or more windows covering the apertures in a shell of the receiver, wherein a first window is constructed of material at least partially transparent to visible radiation but reflecting to infrared radiation, which allows the re-radiation from the hot cavity to be trapped and redirected to the reactor tubes, improving overall efficiency, where the first window is constructed of one or more of the following materials quartz, sapphire, tiled sheets of sapphire, and coated with any number of anti-reflective and reflective coatings to achieve the desired suite of reflective and transmissive properties, and a protective gas purge may be used, and

wherein a chamber of the solar thermal receiver contains additional radiant heat masses to the reactor tubes, which have high temperature (>1400° C) capable storage material that absorb the concentrated solar energy, where the radiant heat masses are used to keep the reactor tubes hot during long periods of off sun, during cyclic up and down times in the plant, as well as keep temperature in the reactor less transient during normal operation when instantaneous solar flux can vary.

17. The chemical plant of claim 2, further comprising:

a hood made of metal or ceramic that overhangs an aperture of the receiver cavity to disrupt convective heat transport between the receiver and the outer atmosphere;

a thin mesh made of transparent high temperature (>1300° C) ceramic or high heat resistance steel material that covers a first aperture in the receiver cavity in order to keep undesirable objects from entering the cavity from the environment; and

wherein the solar-thermal receiver has one or more apertures and no windows.

18. A chemical reactor, comprising:

a thermal receiver having a cavity with an inner wall;

a chemical reactor that has multiple reactor tubes in a downdraft geometry located inside the cavity of thermal receiver, where in the multiple reactor tubes a chemical reaction driven by radiant heat occurs, wherein the chemical reaction includes one or more of biomass gasification, steam methane reforming, methane cracking, steam methane cracking to produce ethylene, metals refining, and CO2 or H2O splitting to be conducted in this chemical reactor using primarily the radiant heat energy;

an indirect radiation driven geometry in the form of the cavity wall of the thermal receiver integrates the chemical reactor, where the inner wall of the cavity of the receiver and the reactor tubes exchange energy primarily by radiation, not by convection or conduction, allowing for the reactor tubes to achieve a fairly uniform temperature profile , and wherein the radiation heat transfer from the inner wall and the reactor tubes drives the chemical reaction, wherein the inner cavity wall at least

partially encloses the multiple reactor tubes to act like an oven, spreading heat flux around through radiation; and

an exit of a gasification zone in the multiple reactor tubes, wherein reaction products have a temperature from the exit of the gasification zone that equals or exceeds 900 degrees C, and 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.

19. The chemical reactor of claim 18, further comprising:

wherein the thermal receiver is 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, where the solar thermal receiver has cavity walls;

wherein the radiant heat driven chemical reactor is driven by the concentrated solar energy and thus is a solar-driven chemical reactor that has multiple reactor tubes;

an aperture open to an atmosphere of the Earth or covered by a window, to pass the concentrated solar energy into the cavity of the solar thermal receiver to impinge on the multiple reactor tubes and inner wall of the cavity;

wherein the chemical reaction is the biomass gasification, where particles of biomass are gasified in the presence of a carrier gas in an endothermic gasification reaction inside the multiple reactor tubes to produce hydrogen and carbon monoxide products; and

a configuration of multiple reactor tubes, wherein the tubes are oriented vertically in the receiver cavity and the biomass particles are introduced at the top of the reactor tubes, entrained by the carrier gas including steam, and are directed by gravity and pressure through a gasification reaction zone of the reactor tubes, where temperatures of operation are clearly delineated with the receiver cavity wall temperatures between 1100 degrees C and 1450 degrees C and a gas temperature from an exit of the gasification reaction zone of the reactor tubes is in excess of the 900 degrees C but not above silica melting temperatures.

20. A solar receiver constructed with a multi-layered insulative outer shell, comprising:

a thin, high temperature (>1400° C) capable, thermal shock resistant insulating inner layer comprising a refractory ceramic fiber materials, where the inner surface of the inner layer is made of a high emissivity refractory material;

a high temperature (>1300° C) capable, high heat capacity, and low-to-moderate thermal conductivity insulating intermediate layer; and

a low density, low thermal conductivity (<0.2 W/m-K at 400° C) insulating layer.

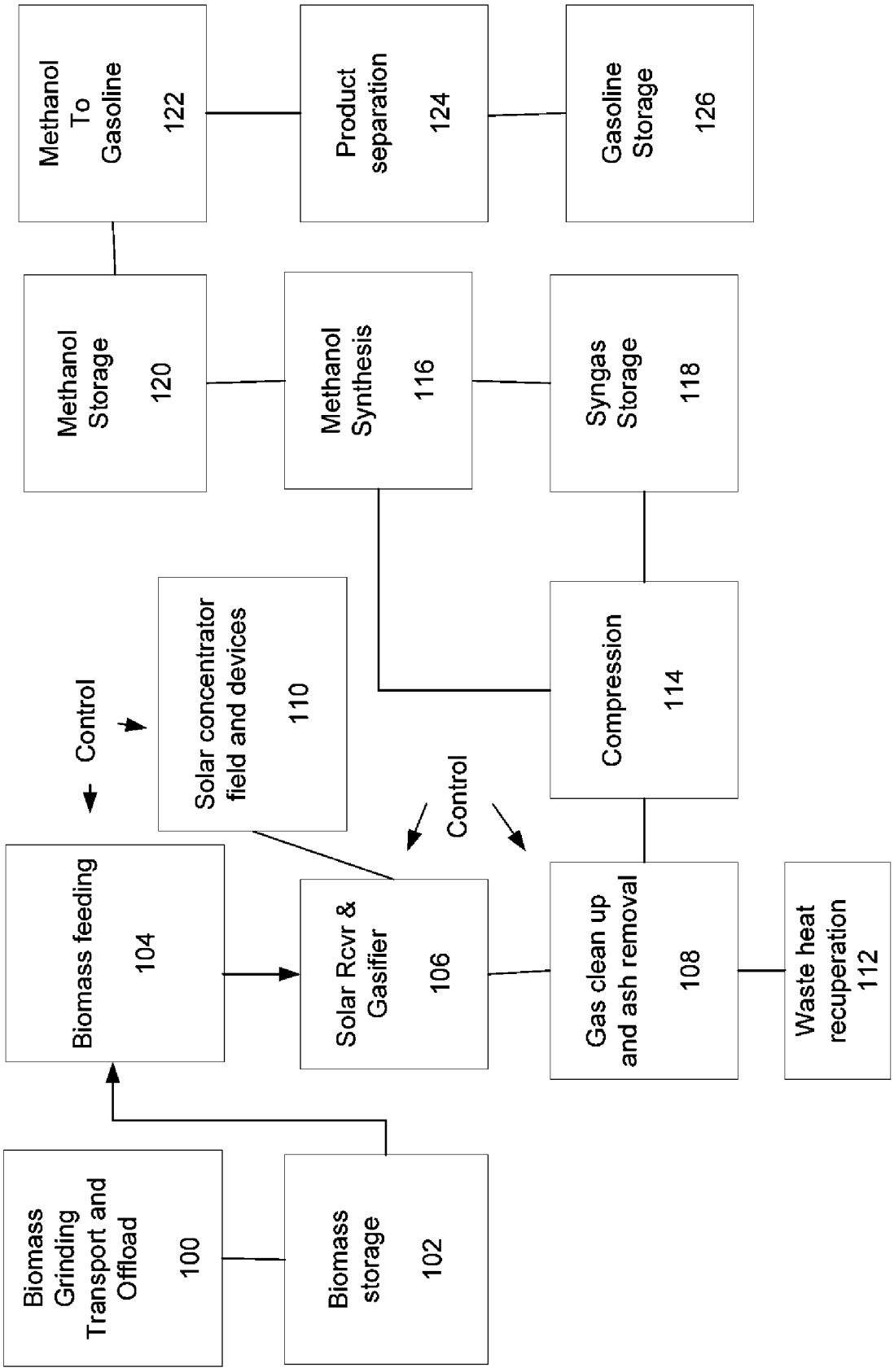

Biomass Grinding Transport and Offload 100
Biomass storage 102
Biomass feeding 104
Solar Rcvr & Gasifier 106
Gas clean up and ash removal 108
Waste heat recuperation 112
Compression 114
Syngas Storage 118
Methanol Synthesis 116
Methanol Storage 120
Methanol To Gasoline 122
Product separation 124
Gasoline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

FIG. 1

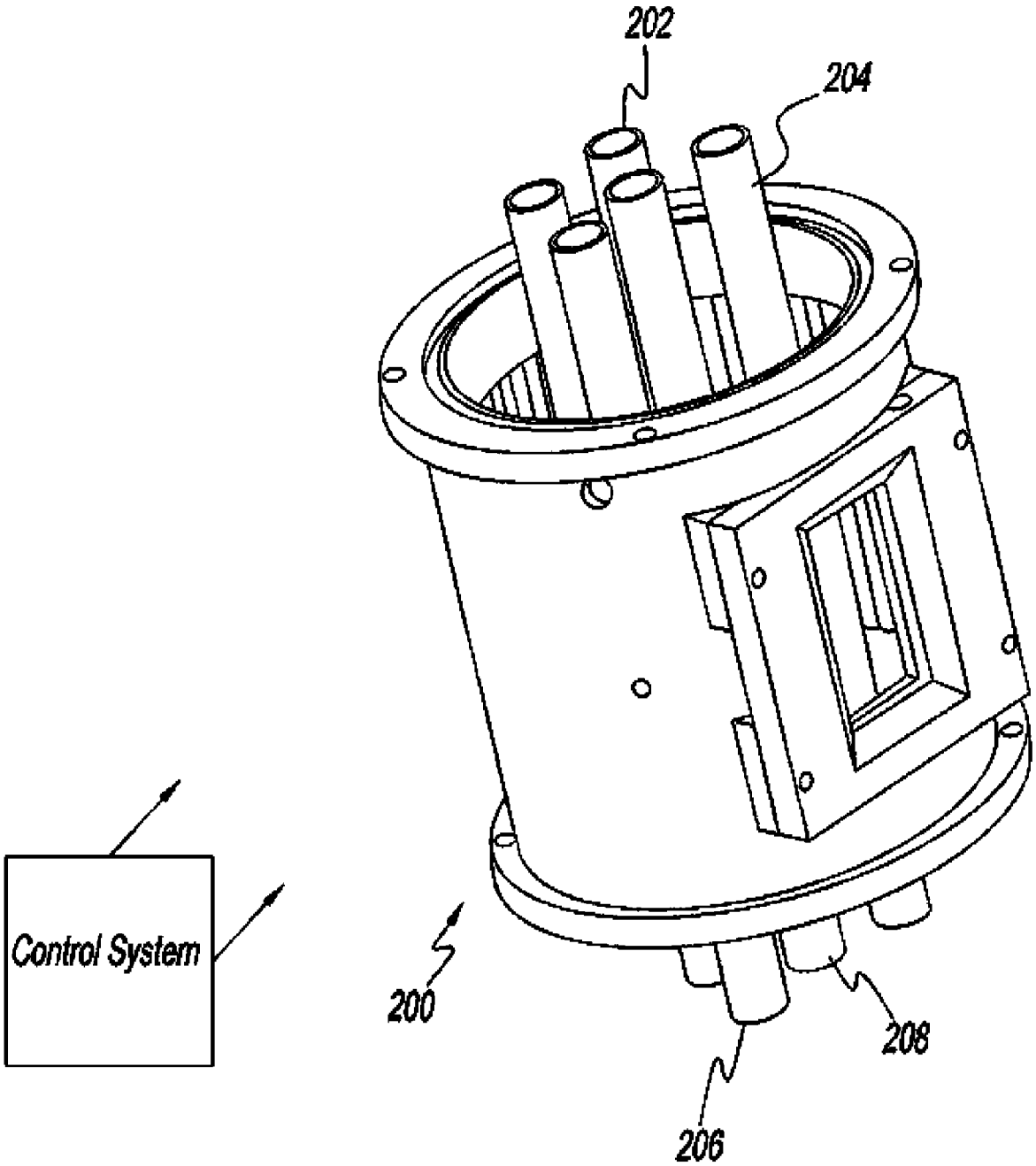


FIG. 2

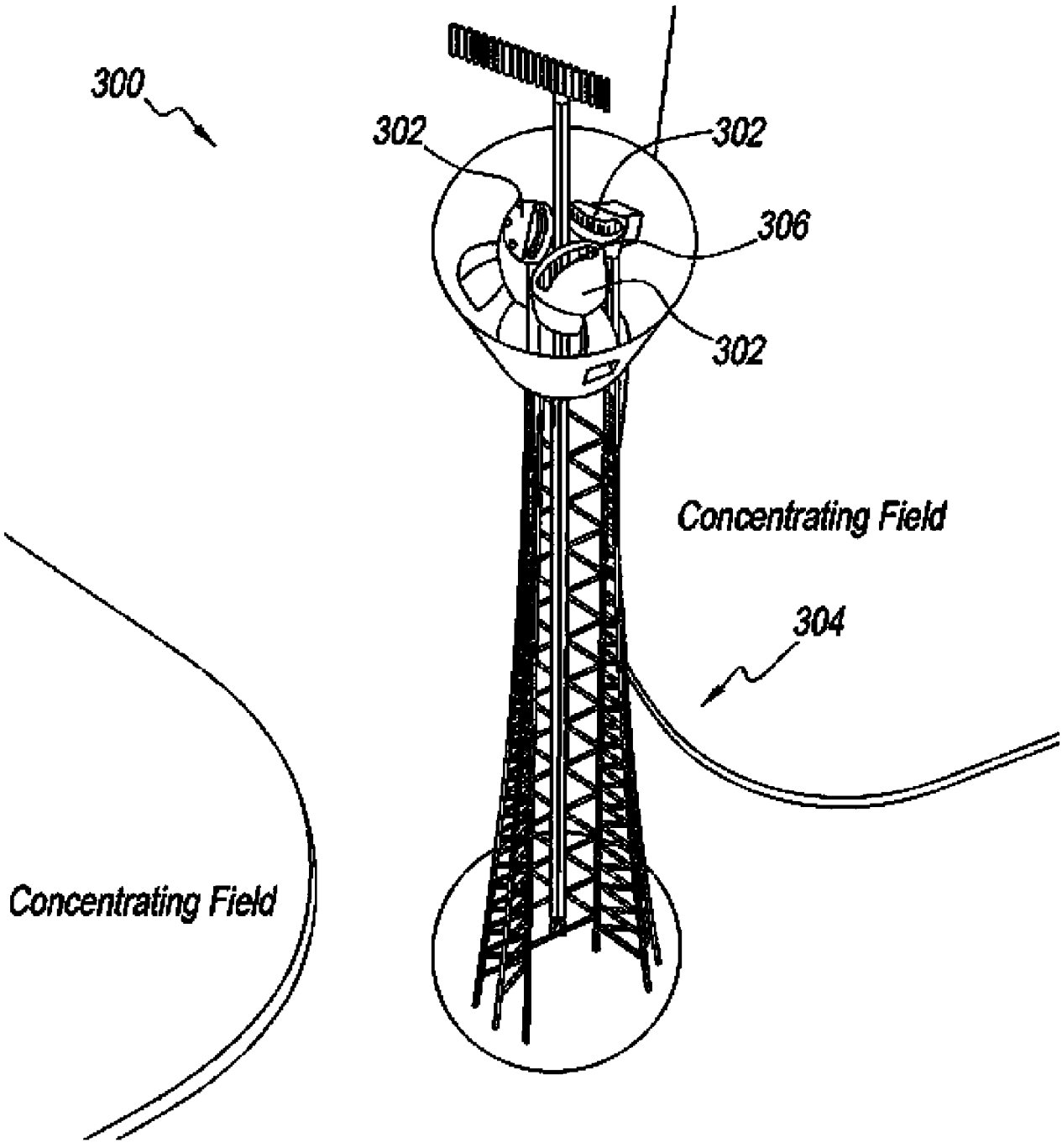

300
302
302
306
302
Concentrating Field
304
Concentrating Field

FIG. 3

Figure 8. AspenPLUS™ Simulation Results (Biomass Methane)

Feed Composition

Biomass	wt%
Cellulose	69.09
Lignin	22.02
Ash	8.89

Reactions

$C_6H_{10}O_5$ (cellulose) + H_2O › 6 CO + 6 H_2

$C_{10}H_{12}O_3$ (lignin) + 7 H_2O › 10 CO + 13 H_2

CH_4 + H_2O › CO + 3 H_2

Material & Energy Balance (T = 1200°C)

	kmol/day	HHV (J/mol)	Energy J/day	Energy GWhr/day	Energy GWhr/yr
Cellulose	854.08	2.83E+06	2.41E+12	0.67	244.68
Lignin	245.04	3.82E+06	9.35E+11	0.26	94.82
CH4	6837.92	8.90E+05	6.09E+12	1.69	617.29
H2	28823.76	2.85E+05	8.23E+12	2.29	834.20
CO	14412.8	3.05E+05	4.40E+12	1.22	446.15

HHV

Reactants **956.78** **GWhr/yr**

H2, CO Products **1280.35** **GWhr/yr**

Q_R = 579 GWhr/yr HHV Products/HHV Reactants = 1.34

FIG. 4

SUBSTITUTE SHEET (RULE 26)

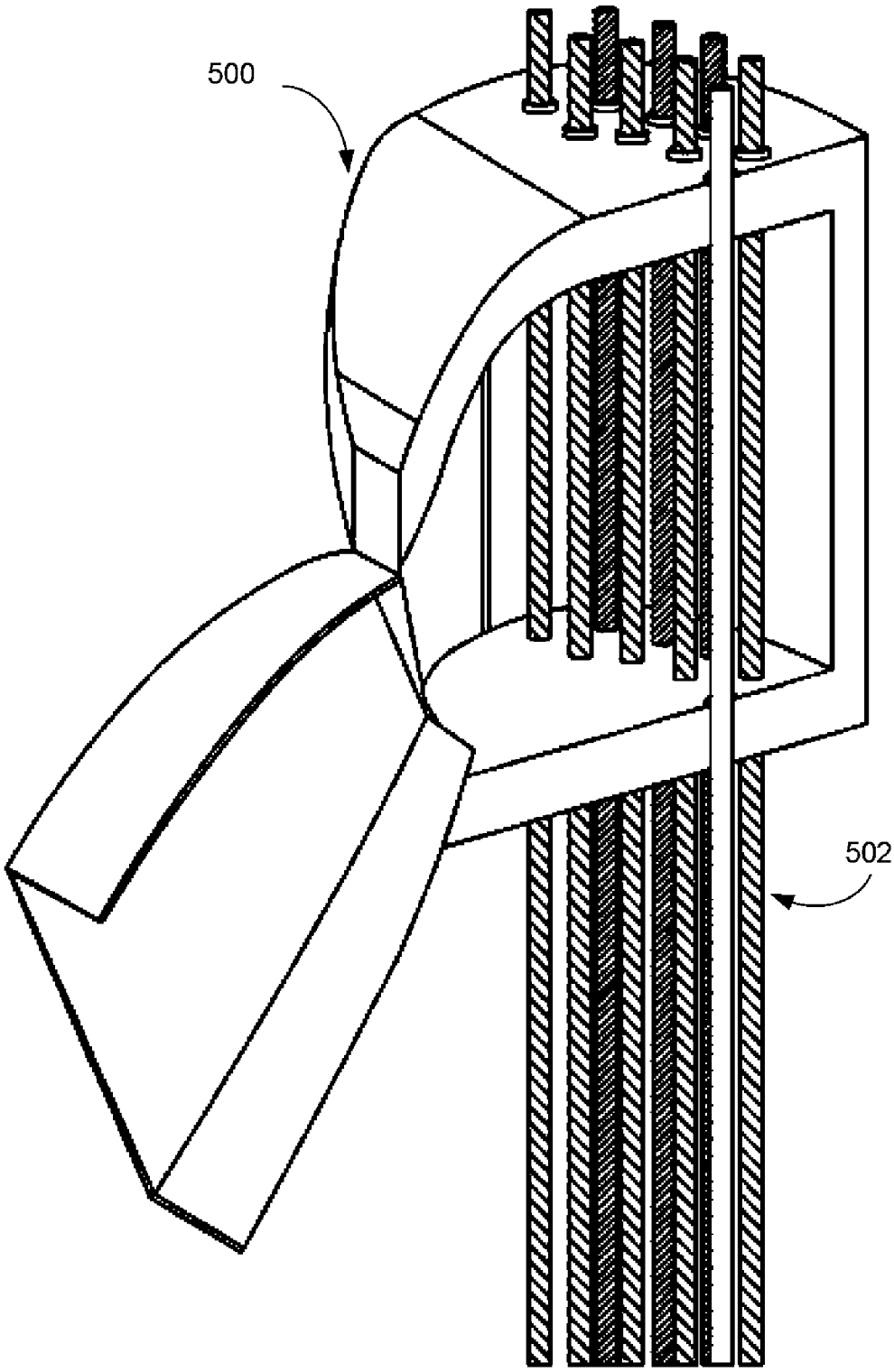


FIG. 5

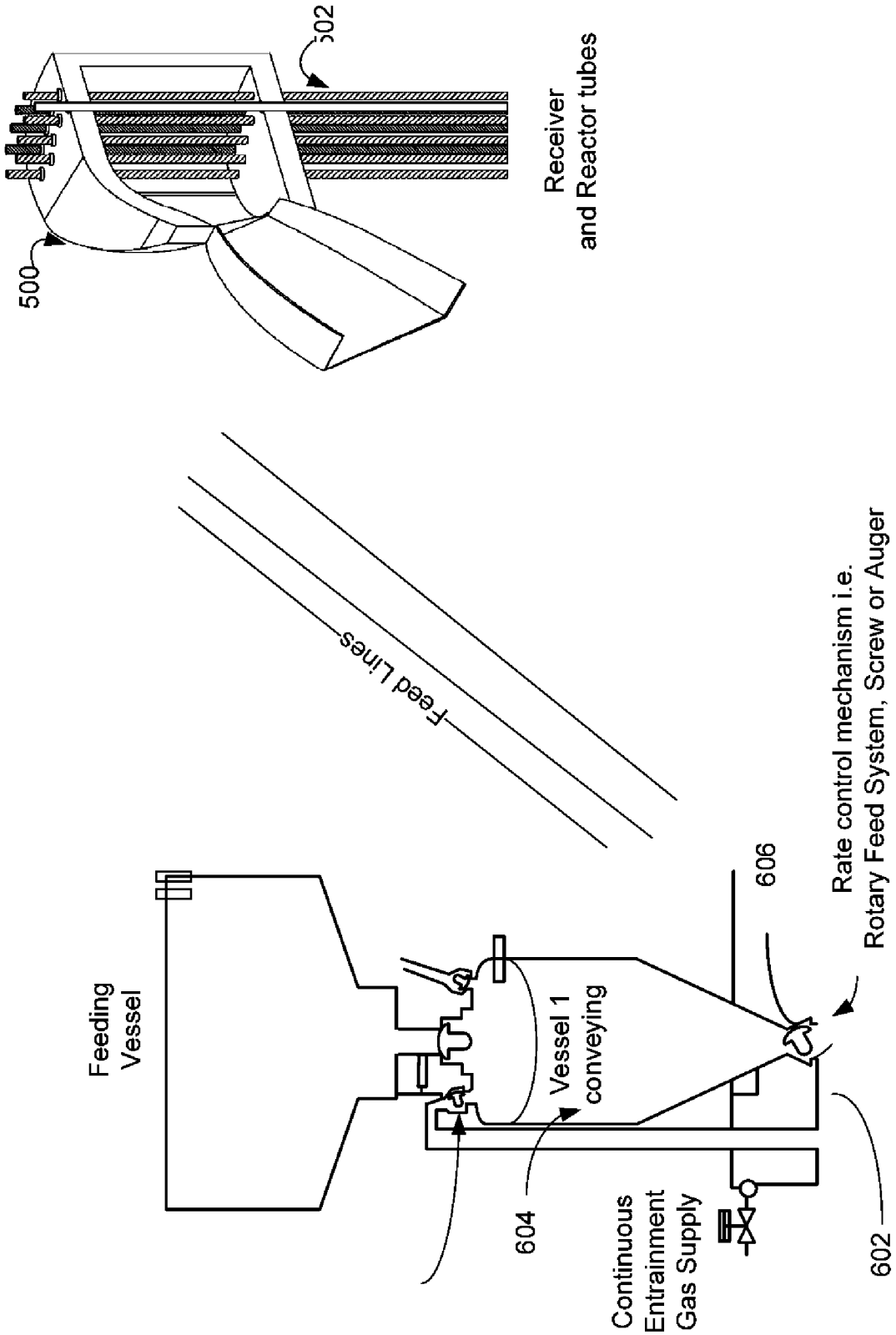

502
Receiver
and Reactor tubes
500
Feed Lines
Feeding
Vessel
Vessel 1
conveying
606
Rate control mechanism i.e.
Rotary Feed System, Screw or Auger
604
Continuous
Entrainment
Gas Supply
602

FIG 6

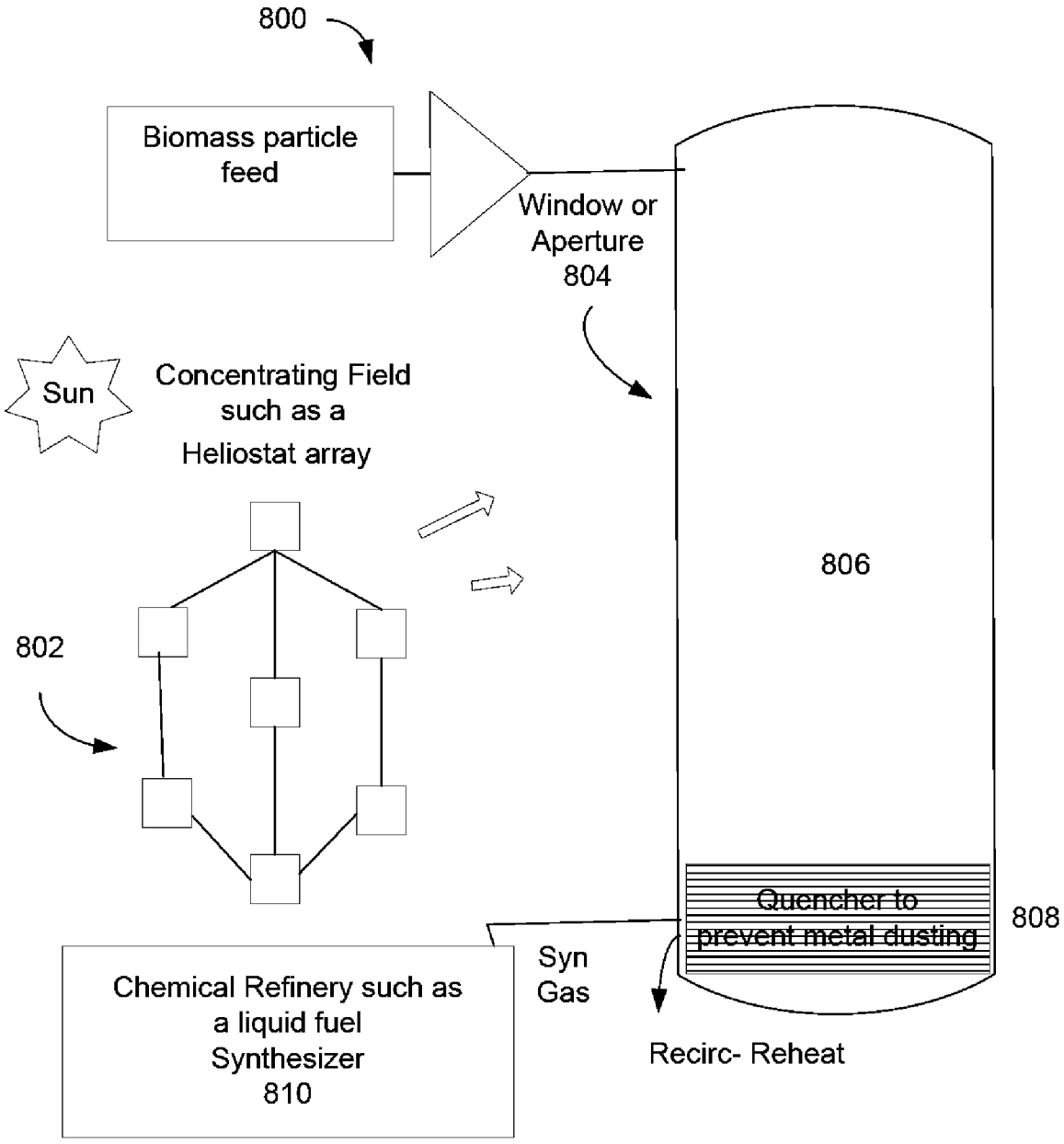

800
Biomass particle feed
Window or Aperture 804
Sun
Concentrating Field such as a Heliostat array
802
806
Quencher to prevent metal dusting
808
Syn Gas
Recirc- Reheat
Chemical Refinery such as a liquid fuel Synthesizer 810

FIG. 7

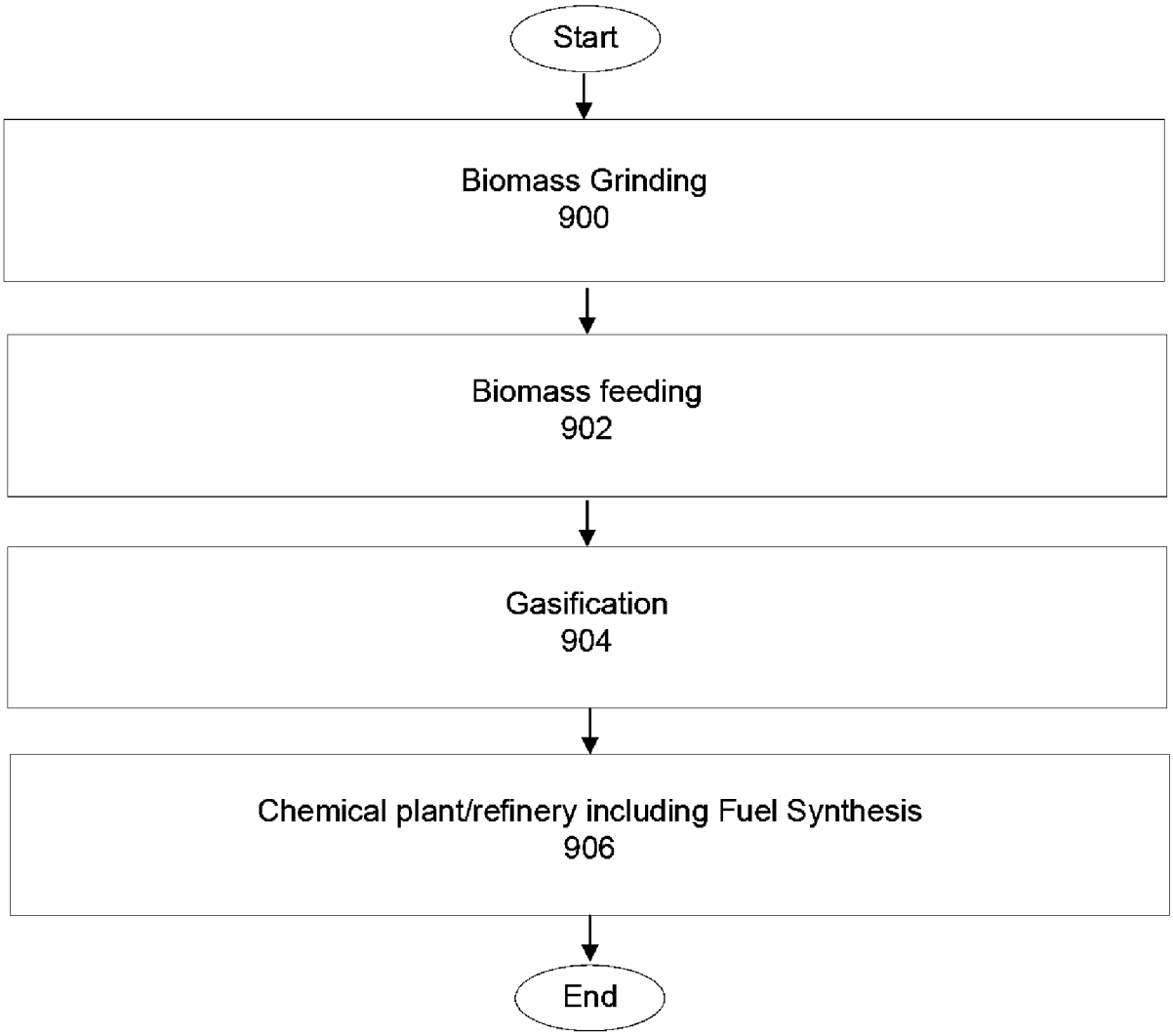

Start
Biomass Grinding
900
Biomass feeding
902
Gasification
904
Chemical plant/refinery including Fuel Synthesis
906
End

FIG. 8

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US 10/37911

A. CLASSIFICATION OF SUBJECT MATTER
IPC(8) - F24H 3/12; C10J 3/48, 3/60 (2010.01)
USPC - 48/89; 48/197R; 432/220
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)
USPC - 48/89; 48/197R; 432/220
IPC(8) - F24H 3/12; C10J 3/48, 3/60 (2010.01)

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
Patents, NPL

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
USPTO - PubWEST; freepatentsonline; Google Scholar. Search terms: biomass carbon carbonaceous chemical city dish energy furnace gas heliostat methane oven reaction reactor solar steam syngas synthesis synthetic tube tubular

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US 2008/0086946 A1 (Weimer et al.) 17 April 2008 (17.04.2008) fig. 2A, 2B; para [0009]-[0011], [0027], [0030], [0034]-[0045], [0060], [0086], [0087], [0090]	1-20
Y	US 4,552,741 A (Melchior) 12 November 1985 (12.11.1985) fig.1; col 1 ln 62 to col 2 ln 2; col 2 ln 25-38, 64-68	1-20
Y	US 2003/0208959 A1 (Weimer et al.) 13 November 2003 (13.11.2003) para [0004], [0008], [0067]	4, 6, 10, 18, 19
A	Mishra et al., Thermal optimization of solar biomass hybrid cogeneration plants, Journal of Scientific & Industrial Research, Vol 65, April 2006, pp. 355-363 entire document	1-20
A	Munzinger et al., Biomass Gassification using Solar Thermal Energy, ANZSES 2006 [downloaded from internet 20 July 2010: http://solar-thermal.anu.edu.au/wp-content/uploads/MunzingerSol06.pdf] 2006 entire document	1-20

☐ 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
20 July 2010 (20.07.2010)	06 AUG 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)