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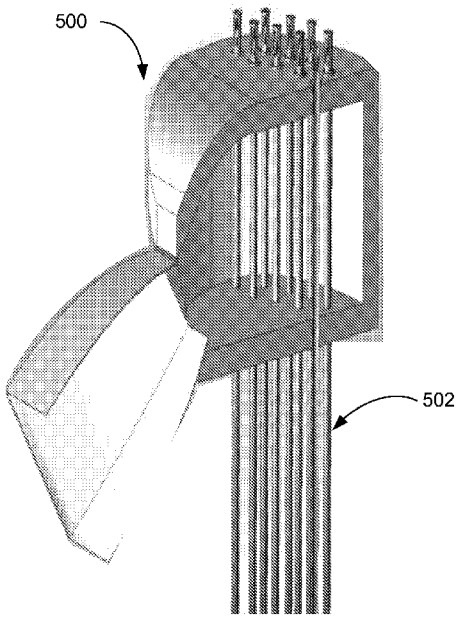


FIG. 5

(57) Abstract: A method, apparatus, and system for solar-driven chemical plant may include a solar thermal receiver to absorb concentrated solar energy from an array of heliostats. Additionally, some embodiments may include a solar driven chemical reactor that has multiple reactor tubes. The concentrated solar energy drives the endothermic gasification reaction of the particles of biomass flowing through the reactor tubes. Some embodiments may also include 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.

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SYSTEMS AND METHODS FOR BIOMASS GASIFIER REACTOR AND RECEIVER CONFIGURATION

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.

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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] The substance/substances initially involved in a chemical reaction are generally called reactants. Chemical reactions are usually characterized by a chemical change in the reactants, which then yields one or more products. Biomass gasification is an

endothermic process that generates syngas; energy must be put into the process to drive the chemical reaction 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 and producing tars. Also, the chemical reactors in such traditional biorefineries are generally engineered to operate at constant conditions around the clock. 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 results in significantly higher yields of gallons of gasoline per biomass ton than previous technologies. As such, the energy source being used to drive the conversion is renewable and carbon free.

SUMMARY OF THE INVENTION

[005] Some embodiments relate to a method, apparatus, and system for solar-driven chemical plant may include a solar thermal receiver to absorb concentrated solar energy from an array of heliostats. Additionally, some embodiments may include a solar driven chemical reactor that has multiple reactor tubes. These tubes can be in a downdraft geometry located inside the solar thermal receiver. Additionally, inside the multiple reactor tubes, particles of biomass may be gasified in the presence of a carrier gas. This gasification process is endothermic, and may produce hydrogen and carbon monoxide products at an exit temperature from the tubes exceeding 1000 degrees C.

[006] In some embodiments, one or more apertures 1) open to an atmosphere of the Earth or 2) covered by a window, may be used to pass the concentrated solar energy into the solar thermal receiver. This energy may impinge on the multiple reactor tubes and the

internal cavity walls of the receiver. Accordingly, the reactor tubes may 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. This can drive the endothermic gasification reaction of the particles of biomass flowing through the reactor tubes. Additionally, high heat transfer rates of the materials making up the cavity walls and the reactor tubes may allow the particles biomass to achieve a high enough temperature necessary for substantial tar destruction and complete gasification of greater than 90 percent of the carbon content of the particles into reaction products including hydrogen and carbon monoxide gas in a very short residence time between a range of 0.01 and 5 seconds.

[007] Some embodiments may also include an on-site fuel synthesis reactor that may be geographically located on the same site as the solar chemical reactor and integrated to receive the hydrogen and carbon monoxide products from the gasification reaction. The on-site fuel synthesis reactor may be configured to use the hydrogen and carbon monoxide products in a hydrocarbon fuel synthesis process to create a liquid hydrocarbon fuel.

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;

figure 2 illustrates a diagram of an embodiment of an example multiple tube reactor;

figure 3 illustrates a diagram of an embodiment of an example solar tower with receivers and heliostat field;

figure 4 illustrates a graph of an embodiment of particle size distribution of representative biomass material;

figure 5 illustrates a diagram of an embodiment of a solar thermal receiver with gasifier tubes;

figures 6a and 6b illustrate block diagrams of embodiments of the entrained-flow biomass feed system;

figure 7 illustrates a diagram of an embodiment of a solar-driven bio-refinery; and

figure 8 illustrates flow diagram of an embodiment of the system.

[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 than 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. Features found in one embodiment may generally be used in another embodiment. The term coupled is defined as meaning connected either directly to the component or indirectly to the component through another component.

[0011] In general, the solar-driven chemical plant includes an entrained-flow biomass feed system feeding a chemical reactor that is feedstock flexible via at least particle size control of the biomass. One example system includes the chemical reactor that supplies an on-site fuel synthesis reactor. The chemical reactor may receive concentrated solar thermal energy from an array of heliostats and this energy can be used to drive chemical reactions including a gasification reaction of the biomass. A solar thermal receiver may also be aligned to absorb concentrated solar energy from the array of heliostats.

[0012] The solar driven chemical reactor may have multiple reactor tubes. These tubes can be in a downdraft geometry located inside the solar thermal receiver. Additionally, inside the multiple reactor tubes particles of biomass may be gasified in the presence of a carrier gas. This may be done in an endothermic gasification reaction to produce hydrogen and carbon monoxide products at an exit temperature from the tubes exceeding 1000 degrees C.

[0013] The concentrated solar energy may impinge on the multiple reactor tubes and the internal cavity walls of the receiver. Accordingly, the reactor tubes may serve the dual functions of 1) segregating the biomass gasification reaction environment from the atmosphere of the solar thermal receiver and 2) transferring energy by solar radiation absorption and heat radiation, convection, and conduction to the reacting particles. This can drive the endothermic gasification reaction of the particles of biomass flowing through the reactor tubes. Additionally, high heat transfer rates of the materials

making up the cavity walls and the reactor tubes may allow the particles biomass to achieve a high enough temperature necessary for substantial tar destruction and complete gasification of greater than 90 percent of the particles into reaction products including hydrogen and carbon monoxide gas in a very short residence time between a range of 0.01 and 5 seconds.

[0014] The carbonaceous biomass material particles being fed from the entrained flow biomass feed system undergo several distinct chemical processes of the gasification reaction prior to exiting the reactor tubes including the following.

[0015] In some embodiments, one or more apertures with or without windows are part of a receiver outer shell that at least partially encloses the multiple reactor tubes. The inside wall of the receiver shell may absorb or highly reflect the concentrated solar energy. This can cause a radiant heat and then generally radiatively convey that heat to the biomass particles in the tubes of the solar driven chemical reactor. Additionally, an inner wall of the receiver cavity may be made of material to allow the receiver cavity to be operated at high (>1200 °C) wall temperatures to enable the high heat transfer rates, rapid reaction kinetics, and high selectivity to syngas.

[0016] Additionally, some embodiments may include an opaque outer wall for each of the reactor tubes. An inner wall of the receiver and the reactor tubes may exchange energy primarily by radiation, not by convection or conduction, in such an embodiment. This can allow for the reactor tubes to achieve a fairly uniform temperature profile even though the concentrated solar energy from the heliostat array or solar concentrators is merely directly impinging on the reactor tubes from one direction. The radiation heat transfer from the inner wall and the reactor tubes may 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.

[0017] Figure 1 illustrates a block diagram of an example process flow. Some embodiments encompass a solar-driven-biomass gasification to liquid fuel/electrical 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.

[0018] 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 compression and the bales are sized to dimensions that may, for example, fit within a standard box car size or shipping container 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. The biomass may be in an embodiment non-food stock biomass. In some cases, food stock biomass might also be processed.

[0019] The biomass may then be stored 102. As needed, the biomass might be fed 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 lines supply the particles of biomass having an average smallest dimension size between 50 microns (um) and 2000 um to the chemical reactor.

[0020] A solar receiver and gasifier 106 may be used to gasify the biomass. An example biomass gasifier design and operation can include a solar chemical reactor and solar receiver to generate the syngas. The chemical reactor's configuration, dimensions, shape,

and material may be varied as well as its cooperation with its solar receiver. Both the chemical reactor and solar receiver form the solar receiver and gasifier 106. Various heliostat field designs and operations to drive the biomass gasifier might be used. Some example systems may include a solar concentrator, secondary concentrator, focused mirror array, etc. to drive biomass gasifier 110.

[0021] Quenching, gas clean up, and ash removal from biomass gasifier 108 may be provided for. 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.

[0022] In various embodiments, synthesis gas may be fed to another technical application. Examples include a syngas to other chemical conversion process. The other chemical of 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 concerted 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.

[0023] Some embodiments can include the on-site chemical synthesis reactor, such as a fuel synthesis reactor, that may be geographically located on the same site as the chemical reactor and integrated to receive the hydrogen and carbon monoxide products from the gasification reaction. 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.

[0024] 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.

[0025] Some embodiments of the systems and methods described herein can include a controller, such as a computerized controller. The tuning and predictive parameters for this controller may be optimized for the full-scale receiver/reactor system, where lag times and response parameters of the heliostat array's flux at the aperture, change in flow rate of the biomass thermal mass are taken in account. The tuning and predictive parameters may also set for the control system tuning parameters at peak, mid, and trough solar energy conditions, as well as operation of the control system with +/- 10% temperature set point through 10 typical solar days.

[0026] Figure 2 illustrates a diagram of an example multiple tube chemical reactor that may be used in a solar driven system. Reactor 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 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. An example amount of five reactor tubes 202, 204, 206, 208 is shown. 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 controlling the rotational speed of the Rotofeed® based on weight change of the biomass in the lock hopper monitored by device such as load cells.

[0027] A solar-driven bio-refinery can include a solar thermal receiver 200 aligned to absorb concentrated solar energy from an

array of heliostats, a set of solar concentrating dishes, or a combination of both. The receiver 200 is the cavity that collects and distributes the solar energy, while the reactors tubes are the individual transport tubes in which the chemical reactions take place. The receiver cavity is the insulating surroundings in which the reactor tubes sit. The reactor tubes are the tubes through which the biomass may flow and then in which the gasification reaction takes place.

[0028] Various embodiments can include a biomass gasifier reactor and receiver configuration that can include various reactor dimensions, shape, and material. For example, a solar driven chemical reactor that has multiple reactor tubes 202, 204, 206, 208 in a downdraft geometry may be used. The multiple reactor tubes 202, 204, 206, 208 can be located inside the solar thermal receiver 200. In the multiple reactor tubes 202, 204, 206, 208 particles of biomass may be gasified in the presence of a carrier gas in an endothermic gasification reaction to produce hydrogen and carbon monoxide products at an exit temperature from the tubes exceeding 1000 degrees C.

[0029] In some embodiments, one or more apertures open to an atmosphere of the Earth or covered with a window may be used to pass concentrated solar energy into the solar thermal receiver 200 to impinge on the multiple reactor tubes 202, 204, 206, 208 and cavity walls of the receiver 200. The reactor tubes 202, 204, 206, 208 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 re-radiation, convection, and conduction. This energy is transferred to the reacting particles to drive the endothermic gasification reaction of the particles of biomass flowing through the reactor tubes 202, 204, 206, 208. High heat transfer rates from the materials making up the cavity walls and the reactor tubes 202, 204, 206, 208 may allow the particles biomass to achieve a high enough temperature necessary

for substantial tar destruction and complete gasification of greater than 90 percent of the carbon content of the particles into reaction products including hydrogen and carbon monoxide gas in a very short residence time between a range of 0.01 and 5 seconds.

[0030] Each of the multiple reactor tubes 202, 204, 206, 208 may provide a chamber for a chemical reaction driven by radiant heat to occur. Additionally, the multiple reactor tubes 202, 204, 206, 208 in this reactor design increase available reactor surface area for radiative exchange to the reactants and inter-tube radiation exchange. The chemical reaction may include one of biomass gasification, steam methane reforming, methane cracking, steam methane cracking to produce ethylene, metals refining, and CO2 capture can be conducted in this reactor using solar thermal energy.

[0031] An example solar-driven chemical plant has a top of the multiple reactor tubes 202, 204, 206, 208. The tubes are oriented vertically in the solar receiver cavity. The biomass particles are introduced at the top of the reactor tubes 202, 204, 206, 208, entrained by the carrier gas such as steam, and are directed by gravity and pressure through a gasification reaction zone of the reactor tubes 202, 204, 206, 208. Temperatures of operation can be 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 202, 204, 206, 208 is in excess of 1000 degrees C. Some embodiments use reactor tubes 202, 204, 206, 208 operating at temperatures of good reactor efficiency that are not above the silica melting temperature of 1600 degrees C.

[0032] In some embodiments, the solar-driven chemical plant includes reactor tubes 202, 204, 206, 208 with an inner diameter sized to allow a substantially uniform gasification of biomass particles from the edges to the center of the tube. Some have a wall thickness

set to withstand at least a 75 psig pressure at 1400 °C on the inside tube walls.

[0033] The one or more apertures may be part of the receiver's outer shell that at least partially encloses multiple reactor tubes 202, 204, 206, 208. The receiver's shell may absorb or highly reflect the concentrated solar energy to cause a radiant heat and then generally radiatively convey that heat to the biomass particles in the tubes of the solar driven chemical reactor. Additionally, an inner wall of the receiver cavity may be made of material to allow the receiver cavity to be operated at high (>1200 °C) wall temperatures. This can enable the high heat transfer rates, rapid reaction kinetics of the very short residence time, and high selectivity of carbon monoxide and hydrogen produced from the gasification reaction for syngas.

[0034] Note, a chemical reactor is the container in which a chemical reaction occurs. Also, the chemical reactor may be a single reactor tube, or a set of reactor tubes. Thus, the chemical reactor may be a single reactor with multiple reactor tubes or multiple reactors each being a single reactor tube, or some other similar combination. Further, different chemical reactions may take place in different reactor tubes of the solar-driven chemical reactor. For example, Steam Methane Reforming may occur in a first set of reactor tubes and biomass gasification may occur in another set of reactor tubes making up the chemical reactor, which is at least partially contained in the solar thermal receiver. Also, different reactions such as SMR and biomass gasification may occur at the same time within the same reactor tube. Additionally, the control system may control the chemical reactions occurring within the reactor tubes via a number mechanisms as described herein. For example, the flow rate of the chemical reactants, such as biomass particles and carrier gas, into and through the reactor tubes is controlled, along with a concentration of each reactant flowing through the reactor tube. The control system may control each

reactor tube individually, or in sets/groups of for example clusters of eighteen tubes, or all of the tubes in their entirety. The shape, orientation, and other features of the reactor tubes may vary as described herein. Note, for contrast purposes, more than one chemical reactor may be located on a common tower such as in figure 3. The example shows a first chemical reactor, a second chemical reactor, and a third chemical reactor contained at least partially within its own associated solar thermal receiver. The first, second, and third chemical reactors located on the same tower may not share a common control system or common solar thermal receiver, and thus, are truly each distinct chemical reactors. However, they all may be fed from some common feed vessels/lock hoppers and/or may share downstream quenching and gas clean up system components.

[0035] In the multiple reactor tubes of the chemical reactor a chemical reaction driven by radiant heat occurs. 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 solar thermal energy from the absorbed concentrated solar energy. A first set of tubes may have a steam methane reforming reaction occurring while a second set of tubes has a biomass gasification reaction occurs.

[0036] Biomass gasification takes place through a number of complex reactions, but these can be grouped into a couple of broad groups. In the first group, volatile components (hydrogen, light alkanes and alkenes) are released at relatively low temperature (200 °C — 600 °C). The reactions are primarily endothermic, and in a falling particle reactor these initial reactions will likely be driven at these low temperatures due to heat transfer limitations. As the reactions proceed, oxygen-deficient char is left behind, in large part from lignin. This component requires higher temperatures (>800 °C)

and an oxidant to gasify. Additionally, the heavier volatile products (tars) from the first series of reactions will break down further into CO and H2 at high temperatures (1000 °C — 1200 °C).

[0037] Thus, the carbonaceous biomass material particles being fed from the entrained flow biomass feed system undergoes several distinct chemical processes of the gasification reaction prior to exiting the reactor tubes including the following.

[0038] 1) Initially, pyrolysis of the carbonaceous biomass particles produces 1) carbonaceous char and 2) volatile components vaporized into gas products. 2) Next, complete gasification of the carbonaceous char including lignin fractions produces 1) gaseous products including carbon monoxide, hydrogen, and tars as well as 2) greater than 99 % pure carbonaceous ash. Next, 3) cracking of the tars, including larger hydrocarbons and aromatic compounds collectively known as tars, occurs at greater than 1000 degrees C to the produce the substantial tar destruction to less than below 200 mg/m^3 and preferably less than 50 mg/m^3 and gasification of greater than 90 percent of the biomass particles into reaction products including hydrogen and carbon monoxide gas. The steps of at least the 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 the low temperature 300 degree C or less preheating by the carrier gas prior to entering the reactor tubes.

[0039] Some embodiments of the solar-driven chemical plant described herein include an opaque wall for each of the reactor tubes 202, 204, 206, 208. In such a system an inner wall of the receiver 200 and the reactor tubes 202, 204, 206, 208 may exchange energy primarily by radiation, not by convection or conduction. This can allow for the reactor tubes 202, 204, 206, 208 to achieve a fairly uniform temperature profile even though the concentrated solar energy is merely directly impinging on the reactor tubes 202, 204,

206, 208 from one direction. The radiation heat transfer from the inner wall and the reactor tubes 202, 204, 206, 208 may 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.

[0040] Because of the high temperatures in the receiver cavity the materials used to make up a wall of the receiver cavity may have mechanical and chemical properties to maintain its strength at high temperatures (between 1100 °C-1500 °C). These materials can have very high emissivity or high reflectivity as well as high heat capacity and low thermal conductivity for the receiver cavity. Additionally, the material of the reactor tubes 202, 204, 206, 208 may possess high emissivity including 0.7 emissivity coefficient or better, high thermal conductivity including 30 watts per meter-Kelvin or better, at least moderate heat capacity of 8 joules per mole–degree Kelvin or better. Further, the material can be resistant to both the oxidizing air environment in the cavity as well as the reducing environment on the tube interior in order to allow the rapid gasification of dispersed falling biomass particulates. This can result in stable ash formation, complete amelioration of tar to less than 50 milligrams per normal cubic meter millimeter, and the production of the hydrogen and carbon monoxide products.

[0041] In some embodiments, the solar-driven chemical plant may include first and second reactor tubes of the multiple tubes 202, 204, 206, 208. The tubes 202, 204, 206, 208 can be materially made of refractory ceramics or metals. The material chosen must have good chemical stability and high strength at high temperatures (1100 °C-1500 °C). Additionally, material with high corrosion and abrasion resistance rates for the particle size of the biomass and steam concentration and good resistance to brittleness from solar flux may be selected. Good thermal shock resistance may provide protection from rapid changes in available solar energy. For example, the

material chosen for tube construction is selected from the group of materials, individually or in combination, including silicon-carbide, Si/SiC composites, silicon-carbide coated graphite, Tungsten, molybdenum, mullite, zirconia, molybdenum with Aluminum Sulfide, Sintered submicron silicon carbide powder such as Hexoloy SA® SiC and Hexoloy SE® SiC, transparent and/or semi transparent sapphire, high aluminum content nickel-base alloys such as Haynes® 214, and refractory ceramics including aluminum oxide (Al203), ceramic matrix composites including melt infiltrated SiC/SiC, and other similar materials. Additionally, the materials may be used individually or in combination. The multiple reactor tubes may have one or more of an added 1) abrasion resistant coating, 2) heat resistant coating (>1050 degrees C), and 3) corrosion resistant coating. The coatings may be added onto the reactor tubes and receiver cavity inner surfaces in a number of ways including sputtering, deposition, and other similar techniques.

[0042] In some embodiments, the material for the tubes may have high oxidation resistance at high temperatures if the receiver cavity is filled with a non-inert gas such as air. Some embodiments include material good at absorbing solar energy, high re-radiating properties via radiation emissivity, and high thermal conductivity. One such material may be silicon carbide protected graphite. The graphite may have thermo-mechanical properties required, such as high temperature capability, excellent thermal conductivity, very good thermal shock resistance and fracture toughness, and high emissivity. A coating of silicon carbide between 0.001" and 0.020" thick can provide oxidation resistance. This coating may be placed on the reactor tube through chemical vapor deposition or through direct siliconization of the graphite and the reactor tubes 202, 204, 206, 208 will be operated at wall temperatures between 1150 °C and 1400 °C.

[0043] Thus, the reactor tubes may be made of silicon carbide coated graphite. The window of the receiver 200 can be made of sapphire and allows the cavity of the receiver 200 to be enclosed. An inert gas supply causes the volume in the receiver cavity to be flooded with an inert gas excluding oxygen from affecting the reactor tubes made of silicon carbide coated graphite.

[0044] The chemical reactor can also be constructed of a transparent material, allowing radiation emitted by the inner cavity wall of the receiver to pass directly through the containing reactor tube and impinge on the reactive particles. This tube could be constructed of any high temperature capable transparent material, and sapphire is a preferred material for this application. Sapphire or a sapphire-based compound has good high temperature properties, high transmission and low absorption in the visible and IR, making it well suited to this application.

[0045] In some examples, the solar-driven chemical plant may have length and diameter dimensions of a gasification reaction zone of each of the reactor tubes 202, 204, 206, 208 that may be sized to give a fast residence time of 0.01 second to 5 second at the gasification temperatures. A first of the multiple tubes may have a different diameter than a second of the multiple tubes. Additionally, the shape of each tube might be a cylindrical shaped pipe or a rectangular shaped pipe.

[0046] In some embodiments, a solar-driven chemical plant may include a downdraft geometry to the multiple reactor tubes 202, 204, 206, 208 in which the biomass particles fall through the downdraft reactor design with no need of disengagement of inorganic compounds or tars generated during the gasification reaction that can deposit downstream and foul critical system components. Accordingly, radiation heat transfer of the cavity walls and tubes surfaces will increase with a fourth power of temperature of the surfaces. At a temperature of greater than the 1000 degrees C these

high heat transfer rates may allow the biomass particles to achieve the high temperatures necessary for tar destruction and complete gasification in the very short residence times (0.01s – 5 s).

[0047] For example, the biomass particles may fall through the downdraft reactor to substantially eliminate an undesirable build-up of solid or liquid matter on the tube walls in the reaction zone which 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 give less surface area for the material to stick on.

[0048] An average smallest dimension size between 50 microns (um) and 2000 um, with a general range of between 200 um and 1000 um may be used for the biomass particles. Additionally, because the surface area of the dispersed particles is so large as compared to the reactor tube surface area, radiant heat may be the primary means of heat transfer. Accordingly, in some embodiments, the use of these small particles gives an increased surface area to greatly increase the gasification reaction rate of the small biomass particles to facilitate the short residence times.

[0049] In some embodiments, the solar-driven chemical plant may include two or more feed lines in the multiple reactor tubes 202, 204, 206, 208. Each feed line may supply a reactor tube to control a dispersion pattern of the biomass particles into its corresponding reactor tube. This may be done 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.

[0050] Various embodiments include an insulation layer around the cavity of the indirect radiation driven geometry, absorbing cavity, and solar thermal receiver. Additionally, multiple reactor tubes 202, 204, 206, 208 may be located in the center of the cavity.

[0051] The thickness of the insulation can be set to control conductive heat losses. The cavity temperature and an average concentration of solar energy at the one or more apertures may control radiative losses. In some embodiments, an aperture design, orientation, and cavity working fluid (buoyancy) are set to control convective losses. The cavity at least partially enclosing the multiple reactor tubes 202, 204, 206, 208 acts like an oven. For example, the cavity may spread heat flux around through radiation and giving a much more even flux profile on the reactor tubes 202, 204, 206, 208 (azimuthally and axially) than the incident solar radiation has. Additionally, an averaging effect on the heat flux radiated from the absorbing cavity walls and multiple tubes occurs within the cavity.

[0052] An axis of the reactor tubes 202, 204, 206, 208 may include a heliostat solar field that focuses the moving Sun to shift the concentrated solar energy sunbeam weighting from West to East across the aperture. This solar energy sunbeam may impinge on the axis of the reactor tubes 202, 204, 206, 208 themselves through the course of each day. Additionally, the oven effect of the cavity along with the particles may tend to average energy amongst themselves at their design volumetric loadings. These volumetric loadings can combine to give the fairly uniform temperature profile and subsequent fairly uniform radial reaction profile of the biomass particles.

[0053] Additionally, the indirect radiation driven cavity reactor may have an aperture that is not covered with a window. In such a system, there is no need for a window (so no need to cool or keep such a window clean) and the reaction environment is sealed off from the cavity environment. While there is some efficiency loss for not directly irradiating the reacting solids, at high temperature, radiation heat transfer makes the required temperature difference very low (as it increases with temperature to the fourth power). The efficiency gains in not needing a window and rapid entrained flow kinetics far outweigh the indirect radiation losses. The solar energy from the

array of heliostats may be directed onto tubes and in the reactor cavity where that energy is required. Note, the cavity, with absorbing walls and multiple tubes has advantages as stated herein.

[0054] A window, for example, is a solid transparent material that allows passage of selected wavelengths of radiation but not passage of solids, liquids, or gases and seals the receiver cavity as opposed to merely a viewing window not involved in the transmission of solar energy to the reactor tubes and cavity. Various embodiments of a solar-driven chemical plant may include a first window that is at least partially transparent to visible radiation but reflecting of IR radiation and no apertures. This can allow the re-radiation from the hot cavity to be trapped and redirected to the reactor tubes 202, 204, 206, 208, improving overall efficiency. Additionally, the window may be constructed of one or more of the following materials quartz, sapphire, tiled sheets of sapphire, or another suitable material and coated with any number of anti-reflective and reflective coatings to achieve the desired suite of reflective and transmissive properties. For example sapphire may be used as a material for the windows that enable the use of graphite material for multiple tubes, wherein the sapphire window may allow the receiver to be enclosed and the volume in the receiver cavity is flooded with an inert gas (e.g. N2 or Ar) excluding O2 from the graphite tubes.

[0055] In some examples of the systems and methods described herein, the solar-driven chemical plant can include length and diameter dimensions of a gasification reaction zone of each of the reactor tubes 202, 204, 206, 208, along with an arrangement and an amount of the tubes that may be matched to an amount of sun concentration from the heliostat field. This can give the residence time of 0.01 second to 5 seconds at the gasification temperatures. For example, a first of the multiple tubes may have a different diameter than a second of the multiple tubes. Tubes exposed to higher radiation fluxes (either direct or indirect), may be smaller in

diameter, and tubes exposed to lower radiation fluxes (either direct or indirect) may be larger in diameter, thereby delivering the same particle heating rates with variable radiation fluxes. Additionally, the shape of each tube might be a cylindrical shaped pipe, a rectangular shaped pipe, or some other shaped pipe. Additionally, the reaction zone in the multiple tubes in which an inner atmosphere of the tubes/the reaction zone may be sealed from and not tolerant to oxygen from an environment present in the cavity.

[0056] Some embodiments may include a substantial axial length of the reactor tube. In this length, the biomass particles may be passed through the reaction zone of the reactor tube along a predetermined path. This path can be substantially coincident with the reactor tube axis. Additionally, the biomass particle reactants may be confined entirely within the reactor tube. In some examples, an arrangement of the cavity may cause high intensity radiant energy from the walls and tubes to be directed through the reactor tubes 202, 204, 206, 208 to coincide with the reaction zone of each reactor tube, either by absorption, conduction, and re-radiation (opaque tubes) or by transmission (transparent tubes).

[0057] Sufficient radiant energy may be absorbed in the reaction zone of the reactor tube to raise the temperature of the reactants to a level required to initiate and sustain the desired chemical reaction of the organic compound. Turbulent flow and/or possible buoyancy driven recirculation, both of which can happen in different operational regimes in the reactor tubes 202, 204, 206, 208 may be used. Additionally, turbulent flow has an average path that follows the axis of a reactor tube.

[0058] A solar-driven chemical plant may also include a chamber of the solar thermal receiver contains additional structures to the reactor tubes 202, 204, 206, 208, which have high temperature storage material that absorb the concentrated solar energy and are used one or more radiant heat masses to keep the reactor tubes 202,

204, 206, 208 hot during long periods of off sun, during cyclic up and down times in the plant, as well as keep radiant temperature in the reactor 200 more stable/less transient during normal operation.

[0059] In various embodiments, a solar-driven chemical plant may include an outer shell of a receiver that has one or more windows. In such an embodiment, an array of heliostats can focus concentrated solar energy thru the windows. Additionally, at least one of the windows may include a French window design with an air/gas curtain design having positive pressure blower or negative pressure vacuum. The windows may be made of sapphire material.

[0060] A solar-driven chemical plant may include a hood made of metal or ceramic that overhangs an aperture of the receiver cavity to minimize disruption of gas flow within the receiver. The receiver is the shell around the reactor tubes 202, 204, 206, 208, which the receiver absorbs or highly reflects solar flux to cause the radiant heat and then generally radiatively conveys that heat to the particles in the tubes of the reactor 200. Additionally, an aperture in the receiver cavity may be covered in very thin mesh made of transparent high temperature plastic or high heat resistance steel material to keep undesirable objects from entering the cavity from the environment.

[0061] The biomass particles may be fed to a multi-tube downdraft solar thermal receiver/reactor, in which the biomass is gasified in the presence of steam at a range of temperatures with the exit temperature exceeding 1000 °C. An alternative design may include updraft reactor or fluid bed reactor. The receiver's use of an indirect radiation, absorbing cavity receiver with multiple tubular downdraft particle reactors is new to the solar thermal processing world (as well as the biomass gasification world).

[0062] Radiant heat transfer differs significantly from convective heat transfer and conductive heat transfer. In radiation heat transfer, both reflectivity and emissivity of materials are generally wavelength dependent. The temperature determines the wavelength distribution

of the electromagnetic radiation as limited in intensity by Planck's law of black-body radiation. Thus, whether the radiation is coming from the Sun or a separate radiant heat source is a significant design consideration because the reflectivity and emissivity of the tube walls controls its ability to radiate the heat (radiant heat transfer) to the reacting particles or inert particles fed to transfer energy to a reactive gas.

[0063] Some embodiments may radiantly transfer heat in sufficient quantity in order to sustain the desired chemical reaction of the reactant gas, with the electromagnetic radiation coming from the Sun/solar radiation. Additionally, the receiver reactor may have an emissivity high in both the visible and IR ranges (0.3 – 10 micron wavelength).

[0064] An insulating cavity approach is essentially a blackbody cavity. Conductive losses can be controlled by changing the thickness of the insulation, and convective losses can be controlled through aperture design, orientation, and cavity working fluid (buoyancy). The key advantage of the blackbody cavity is control of the radiative losses, which are entirely determined by the cavity temperature and the average concentration at the aperture. The cavity acts like an oven, spreading heat flux around through radiation and giving a much more even flux profile on the reactor tubes 202, 204, 206, 208 (azimuthally and axially) than the incident solar radiation has. This is a major advantage for a solar field, where the moving sun shifts the beam from West to East weighting across the aperture through the course of each day.

[0065] In an embodiment, the amount of reactor tubes present in the cavity of the solar thermal receiver will be in a preferred range of 120-150 reactor tubes, with a range encompassing as few as 30 reactor tubes and as many as multiple 100s. Each reactor tube will have the same size diameter the rest of the reactor tubes. The geometric arrangement of the multiple reactor tubes relative to each

other will be arc pattern with probably more than one row. The shape of each individual reactor tube will all be cylindrical. The expected size, shape, and orientation of the aperture in the receiver relative to the concentrated solar energy coming from the array of heliostats or solar concentrating dishes will be approximately a 7 meters by 7 m square. The length and diameter dimensions of the gasification reaction zone in the reactor tubes is the inner diameter of the tubes will be 6 inches and stretch the full length of the tube such as 9 meters long.

[0066] Figure 3 illustrates a diagram of an example solar tower 300 with receivers 302 and heliostat field 304. A solar tower 300 may be used in the solar-driven bio-refinery with the entrained-flow biomass feed system. The feed system can be feedstock flexible via, for example, particle size control of the biomass.

[0067] Multiple solar thermal receivers 302 may be on a common tower 300. Each receiver 302 contains a chemical reactor 306. A chemical reactor 306 in each receiver 302 receives concentrated solar thermal energy from an array of heliostats 304 or concentrating dishes. The chemical reactor 306 can be, for example, a multiple reactor tube, downdraft, solar driven, chemical reactor 306, which receives concentrated solar thermal energy from the array of heliostats 306. The solar-driven bio-refinery may also include a biomass feed system that has the feed lines to each of the reactor tubes in a multiple tube chemical reactor 306. Biomass may be fed to the solar reactor 306 in an operation including three parts: biomass transport and preparation for feeding to the solar tower reactor 300, 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.

[0068] The solar thermal gasifier has a downdraft geometry. The tubes are oriented vertically in the solar receiver cavity, and are, for example, 16" in inner diameter with, for example, a one inch, wall

thickness to withstand at least 75 psig pressure on the inside tube walls.

[0069] An absorbing solar receiver cavity exists in which the gasification reactor tubes run vertically. Solar energy enters the cavity through an aperture open to the atmosphere and impinges on the reactor tubes and the cavity walls. The walls and tubes exchange energy primarily by radiation, allowing for the tubes to achieve a fairly uniform temperature profile even though solar energy is only impinging on the tubes from one direction.

[0070] An example receiver cavity is a sectioned cylinder, with an internal diameter of 10 m. The inside walls of the receiver cavity are constructed of refractory alumina plate. Outside of this plate layer can be alumina (or similar material) fiber insulation, which can have a thickness of, for example 24 cm. The receiver may be contained by a first structural carbon steel shell with a thickness of, for example, 0.090" wall thickness, where there is an air gap with a thickness of, for example, 2", beyond this first carbon steel shell. A second carbon steel shell of the same thickness as before may be used to form the boundary of the air gap. This second carbon steel shell may further contain the conductive losses from the cavity. The thickness of the insulation, air gap and steel shells has been designed so as to limit conductive losses from the cavity to less than 2% of the concentrated solar energy incident from the heliostat array on the aperture or window of the solar thermal receiver. The top and bottom surfaces of the cavity are similarly constructed.

[0071] In another example, the receiver 302 will ensure uniform distribution of energy across all the tubes. The tubes could all be of the same diameter and be fed by the same biomass feed rate, thereby all giving the same productivity. Similarly, the energy distribution may not be uniform across the receiver 302, yet the tubes are all to be fed with a same feed rate and give the same productivity. The way to achieve this would be to have tubes of

different diameters, sized to deliver the same heat rates according to variable fluxes. The variability in the solar flux within the receiver 302 may also be addressed by controlling a corresponding variability in the individual feed rates through the equivalent tubes. Thus, many methods exist like the examples given above for changing the number, size diameter and length of the tubes and biomass feed rate per tube to address different flux environments.

[0072] The indirect simple tubular reactor design has a simple design, which is not only less difficult to design, but less likely to fail during operation. The feedstock flexibility clearly gives an economic advantage over processes that are limited to one or a few available feedstocks. By heating the reactor tubes with solar energy (which re-radiate to the particles), the problem of generating heat for the reaction and designing the reactor to conduct the reaction (essentially the endothermic/exothermic balancing problem) is eliminated. The solar energy can be directed to where it is required.

[0073] A falling particle reactor is an efficient way to get thermal energy into reacting solid particulates (or gases). Heat transfer from the reactor tubes to the reacting and/or non-reacting particles can occur by particle wall contact conduction, convection from the surrounding gas heated by the tube wall, or radiation from the tube wall or other surrounding particles. Even the heated non-reacting particles can be used for many purposes discussed in this document. At moderate temperatures, convection and conduction dominate when transferring energy to a fluid, but these require large amounts of surface area to be effective. To get around this problem, radiation heat transfer is required, which requires temperatures above 1000 degrees C (and preferably above 1200 degrees C). However, if the surface area being radiated to is small, local temperatures will get high and efficiencies will be low. A dispersed particle reactor solves this problem by greatly increasing the receiving surface area (it is essentially the surface area of the particles), shifting the limitation to

the radiating tube. The particles tend to average energy amongst themselves at our volumetric loadings, giving a uniform radial reaction profile. If it is the gas that is desired to be heated (for steam reforming of methane or methane cracking, for example), inert particles can be used as radiation receivers and convection can be used to drive energy from the said particles to the gas. Because the surface area of the particles is so large (as compared to the tube surface area) and at a high temperature, the particle-to-gas convection heat transfer is no longer a limitation.

[0074] Additionally, the use of small particles increases the surface area for reaction. As reactions with gas phase components (e.g. steam, CO2) are surface area specific, the increased surface area greatly increases the reaction rate.

[0075] Note, in an embodiment, a heat transfer aid in the form of a particulate flow of inert particles may be used to heat the reactant gases. The flow of inert particles is passed through the chemical reactor through the riser of a circulating fluidized bed system. A fluidizing gas source supplies a reactant gas that entrains the inert particles and the particles of biomass flow upward through the reactor tubes. A return tube for the circulating fluidized bed then passes through the solar thermal receiver with some of the exit products. The reactant gas flows counter-currently or co-currently with the downward traveling inert particles and biomass particles.

[0076] In an embodiment, the flow of inert particles is mechanically metered and entrained in the gas flow and fed either upward or downward through the reactor tubes. A gas-solid separator such as a cyclone is coupled to the chemical reactor. The inert particles are mechanically separated from the product gas stream and recovered for reuse. The heat transfer aid used to heat the reactant gases can also be a non-circulating fluidized bed of inert particles in which the reactant gas is the fluidizing gas.

[0077] Another heat transfer aid may be in the form of a structured packing used to heat the reactant gases . The structured packing is one or more of the following: reticulate porous ceramic (RPC) foam, a ceramic monolith, or ceramic tubes inside each reactor tube. The packing can be configured for radiation as the primary mode of heat transfer to the heat transfer aids from the reactor tube walls. Conduction, convection, or some combination of the two is secondary modes of heat transfer.

[0078] Figure 4 illustrates a graph of cumulative particle size distribution. The graph illustrates the weight percentage below *Y%* for a given screen size in microns. Example materials are illustrated including knife-chopped rice straw and miscanthus stems. The smaller the size of the particle of the various types of biomass, the less difference in the way the feed system and reactor view particles from different types of biomass.

[0079] 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 chemical plant. 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.

[0080] The solar driven chemical reactor that has multiple, for example, vertically oriented reactor tubes in a downdraft configuration, fluidized bed, or other reactor configuration.

[0081] As discussed, a window may be a solid transparent material that allows passage of selected wavelengths of radiation but impervious to solids, liquids, or gases, to pass the concentrated solar energy into the solar thermal receiver to impinge on the multiple reactor tubes and cavity walls of the receiver. The reactor tubes serve the dual functions of 1) segregating the biomass gasification reaction environment from the atmosphere of the receiver and 2)

transferring solar energy by absorption and re-radiation, convection, and conduction. The energy transfer to the reacting particles can drive the endothermic gasification reactions of the particles of biomass flowing through the reactor tubes. Additionally, high heat transfer rates from the inner cavity walls through the tubes may allow the particles biomass to achieve a high enough temperature necessary for substantial tar destruction and complete gasification of greater than 90 percent of the carbon content of the biomass particles into reaction products including hydrogen and carbon monoxide gas in a very short residence time between a range of 0.01 and 5 seconds.

[0082] In some embodiments, the reactor uses the high surface area of the biomass particles to facilitate a rapid gasification reaction due to efficient heat and mass transfer. The gasification reaction is caused by the efficient heat transfer, which is a result of receiver configuration and temperature, and particle dispersion pattern.

[0083] The bio-refinery may produce fuels, chemicals, or both. For example, the integrated chemical plant may make fine chemicals from this bio-refinery as well as the liquid hydrocarbon fuel.

[0084] In some embodiments, the solar-driven chemical plant may include one or more open apertures or windows that might be part of an outer shell of the receiver. The receiver may at least partially enclose the multiple reactor tubes. Additionally, the inner wall of the receiver may absorb and highly reflect the concentrated solar energy from the array of heliostats to radiatively transmit that radiant heat to the biomass particles in the reactor tubes of the solar driven chemical reactor. In some embodiments, heat may transfer through the tube walls by conduction.

[0085] In some embodiments, a material making up the inner wall or at least coating the inner wall of the receiver cavity may have mechanical and chemical properties to retain its structural strength at high temperatures (between 1100 °C-1500 °C). This material may

also have very high emissivity (ε>0.8) or high reflectivity (ε<0.2) as well as high heat capacity (>200 J/kg-K) and (<1 W/m-K) low thermal conductivity. The material for the reactor tubes may possess high emissivity (ε>0.8), high thermal conductivity (>1 W/m-K), and moderate to high heat capacity (>150 J/kg-K). Additionally, it may be resistant to the oxidizing air environment in the cavity and the reducing environment of the biomass gasification reaction in order to allow the rapid gasification of dispersed falling biomass particulates with a resultant stable ash formation.

[0086] Some embodiments may allow for amelioration of tar to less than 50 milligrams per normal cubic meter, and the production of the hydrogen and carbon monoxide products. Additionally, an inner wall of the receiver cavity may be made of or coated with an absorbing solar energy material rather than the highly reflective material.

[0087] For the cavity walls, some embodiments may use a material that has either very high emissivity or high reflectivity, low thermal conductivity, and high heat capacity. For the reactor tubes, some embodiments may use high emissivity, high thermal conductivity, and moderate to high heat capacity materials. Generally, the reactor tubes might need to be able to handle the oxidative environment on only one side and the steam plus reducing environment on the other. Additionally, usually only the reactor tubes need to withstand pressure. The receiver wall might only be oxidation resistant and strong enough so as not to fall apart under its own weight at temperature.

[0088] Figures 6a and 6b illustrate block diagrams of embodiments of the entrained-flow biomass feed system 600. Different types of feed systems may be used in conjunction with biomass into reactor, for example, drop tube, total solid fed into the reactor, slurry fed into the reactor, a moveable bed in the reactor, or combinations of these schemes.

[0089] One example solar-driven chemical plant may include an entrained-flow biomass feed system 600 that is preceded by a conveyer to bring bales of the biomass to a grinding system. The grinding system has a bale cutter/debaler, which debales the biomass. A mechanical cutting device then grinds the biomass into particles, which are to be fed into the solar driven chemical reactor. The grinding system supplies 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.

[0090] As illustrated in FIGs. 6a and 6b, the entrained-flow biomass feed system 600 can include a pressurized lock hopper 604 that feeds the biomass to a rotating metering feed screw 602 and then into an entrainment gas pipe at the lock hopper exit 606. The particles of the biomass are distributed into multiple entrainment gas lines by a flow splitter to feed the two or more reactor tubes making up the solar-driven chemical reactor. The entrainment gas for the entrained-flow 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.

[0091] 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 the rotational rate of a feeding screw 602 at a base of the lock hopper 604, which responds to a feed demand signal received from the computerized control system based on the weight change of the biomass in the lock hopper monitored by a device such as load cells.

[0092] 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 may be located at the base of the lock hopper and its rotational speed can be controlled by a computerized control system to respond to feed demand of the system. The control system hardware may be one or more of a Programmable Logic Controller, via different data communication protocols using Personal Computer, Macintosh, CNC, neural nets, analog devices, with accompanying software applications and algorithms scripted to perform various functions, or various combinations of these systems. In an embodiment, the computerized 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.

[0093] Additionally, some systems may include a computerized control system configured to balance the amount of biomass particles flowing in each of the reactor tubes to an amount of solar energy available via, for example, a 2-phase control system. Such a system can be used to control flow in the individual reactor tubes by controlling a rotational rate of a screw/auger of a lock hopper feeding the biomass. Additionally, an amount of compression of a pinch valve configuration may be applied to a conduit such as a hose, tube, pipe, or other vessel capable of conveying materials section of each

individual feed line that the biomass particles are flowing through to provide some control of flow, for example.

[0094] In some embodiments, a solar-driven bio-refinery may include an entrained-flow biomass feed system. The entrained-flow biomass feed system may be preceded by mechanical cutting device to grind and pulverize biomass to a particle size controlled to an average smallest dimension size between 50 microns (um) and 2000 um, with a general range of between 200 um and 1000 um. Additionally, the entrained-flow biomass feed system may supply a variety of biomass sources fed as particles into the solar driven chemical reactor without changing the reactor's structure. (In some examples, non-food stock biomass might be used.) Additionally, the variety may include three or more types of biomass that can be fed, individually or in combinational mixtures, from the group consisting of rice straw, rice hulls, corn stover, switch grass, non-food wheat straw, miscanthus, orchard wastes, sorghum, forestry thinning, forestry wastes, energy crops, source separated green wastes and other similar biomass sources. The biomass may be in a raw state or partially torrefied state, as long as a few parameters are controlled including particle size of the biomass and operating temperature range of the reactor tubes. A mechanical agitator in the lock hopper or feeding vessel can be used to enhance the bulk flow of biomass particles that might otherwise tend to bridge in the vessel due to Van der Waal's forces.

[0095] The reactor tubes are configured to generate syngas from one or more of the following: (i) biomass particles and steam (ii) biomass particles, methane, and steam, (iii) methane and steam (SMR). The different reactor tubes within the same receiver are configurable to operate with the different chemical reactants listed above. Also, at least two or more different types of biomass materials might be used in the same reactor tube geometry in some example systems. This can obviate any need for a complete

reengineering when a new type of biomass feedstock is used. It will be understood that multiple feed stocks could be used simultaneously or one feedstock might be used at a time.

[0096] Figure 7 illustrates a diagram of a solar-driven chemical refinery 800. In such a system, solar power 802 passes through a window or open aperture 804 to heat a reactor chamber 806. A quencher 808 may be used to prevent undesired reactions. As illustrated, biomass particles flow into the system at 810 and syngas flows out. Additionally, a heat exchange may occur between the biomass particles and the syngas.

[0097] Some embodiments of the solar-driven chemical plant may include insulation on an outside shell of the receiver to reduce heat loss during operations and overnight during shutdown. The insulation may be thick enough to keep conductive losses to less than 10% during operations. Examples of insulation that might be used include one or more from the group consisting of ceramic brick, ceramic blanket, and combinations of the two.

[0098] In various embodiments a small boiler or resistance heaters may be connected to the outside wall of the receiver shell of the receiver to aid in temperature control of the chemical reactor. The boiler or heater may aid in temperature control during operations, as well as during shutdown and start up operations.

[0099] In some examples a quench zone may be included immediately downstream of the exit of the chemical reactor to immediately and rapidly cool at least the hydrogen and carbon monoxide reaction products. This cooling may occur within 2-10 seconds of exiting the reactor, for example. The cooling may be to a temperature below a level at which undesired chemical reactions occur at negligible rates.

[00100] A return tube may also exist at the exit of the chemical reactor. The return tube passes outside the receiver for the multiple

reactor tubes to recycle all or a portion of the products of the gasification reaction from the exit of the chemical reactor.

[00101] The array of heliostats 802 can be used to focus light onto a window 804 to the reactor 806. In reactor 806 biomass particles can be reacted away to syngas, which in turn can be synthesized into liquid fuel in liquid fuel synthesizer 808.

[00102] Some embodiments of the solar-driven chemical plant may be configured such that, at an exit of the gasification reaction zone in the reactor tubes of the chemical reactor, the biomass gasification products from the multiple tubes may be joined into several large tubes. Additionally, then water or methanol is injected into the large tubes to rapidly cool the product gases and, in the case of water injection, provide steam for the water gas-shift reaction necessary to achieve a proper H2 to CO ratio between 2.0 and 2.7 for syngas used by the on-site fuel synthesis reactor in the fuel synthesis process.

[00103] In some embodiments, a high solar flux concentration from the heliostat field may provide or give equal to or greater than three MW per meters squared of solar energy at the apertures. This may give the receiver cavity a capacity of at least 2000 kW and generally around 60,000 kW. The multiple tube construction of the cavity may increase the surface area for radiative transfer to the biomass particles. Additionally, the shape of the reactor tubes may be substantially rectangular, which also yields a higher surface area for equivalent volume than cylindrical shaped tubes.

[00104] As the gasification is performed through indirect heating, the cavity and tube walls must be able to efficiently transfer solar energy to the reacting particles. Residence times greater than 2 seconds will be more than sufficient for the biomass to be gasified at temperatures between 500 °C and 1000 °C. The key limiting factor in receiver design is heat transfer from the indirectly heated cavity wall and the reacting particulates.

[00105] Some embodiments of a solar-driven chemical plant may include inert heat absorbing particles. Some examples of such particles may include silica, Carbo HSP, or other proppants. These can be entrained along with the biomass particles and heat energy to drive the chemical gasification reaction of the biomass particles comes from the following three sources 1) the heat absorbing particles, 2) the reactor tubes, and 3) an inner wall of the cavity and all that heat energy is derived from the concentrated solar energy. Additionally, an ash and particle storage mechanism may be used. In such a mechanism, the inert heat absorbing particles and ash remnants of the biomass exit the solar reactor at the greater than 1000 degrees C.

[00106] Some embodiments may also include a gas-solid separator. The separator can be configured to separate the inert heat absorbing particles and ash remnants from the gas products that then can be transferred into the ash and particle storage system. The particle storage system may store these particles and ash remnants to recover their heat in order to heat a working fluid that drives an electricity generation apparatus or other apparatus used in operating heat based processes. Examples of such heat recuperation include preheating water, preheating gas streams, and other thermodynamic work.

[00107] Figure 8 illustrates a flow diagram of an embodiment of the system. In step 900, 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 debaled biomass into particles, which are to be fed into the solar thermal gasifier. The ground biomass particles have an average smallest size between 500 um and 1000 um, and are loaded into the lock hopper system with a standard belt or vacuum conveyer.

[00108] In step 902 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.

[00109] In step 904 gasification occurs. For example, in some embodiments, concentrated solar thermal energy drives gasification of the particles of the biomass to generate at least hydrogen and carbon monoxide products from the gasification reaction.

[00110] In step 906 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.

[00111] The methods and apparatuses of the invention in some cases may be implemented using computer software. If written in a programming language conforming to a recognized standard, sequences of instructions designed to implement the methods can be compiled for execution on a variety of hardware platforms and for interface to a variety of operating systems. It will be appreciated that a variety of programming languages may be used to implement the teachings of the invention as described herein. Furthermore, it is common in the art to speak of software, in one form or another (e.g., program, procedure, application, driver, etc.), as taking an action or causing a result. Such expressions are merely a shorthand way of

saying that execution of the software by a computer causes the processor of the computer to perform an action or produce a result.

[00112] A machine-readable medium is understood to include any mechanism for storing or transmitting information in a form readable by a machine (e.g., a computer). For example, a machine-readable medium includes read only memory (ROM); random access memory (RAM); magnetic disk storage media; optical storage media; flash memory devices, etc.

[00113] While some specific embodiments of the invention have been shown the invention is not to be limited to these embodiments. The invention is to be understood as not limited by the specific embodiments described herein, but only by scope of the appended claims.

CLAIMS

What is claimed is:

We claim:

1. A solar-driven chemical plant, comprising:

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;

a solar driven chemical reactor that has multiple reactor tubes in a downdraft configuration located inside the solar thermal receiver, where in the multiple reactor tubes particles of biomass are gasified in the presence of a carrier gas in an endothermic gasification reactions to produce hydrogen and carbon monoxide products at an exit temperature from the tubes exceeding 1000 degrees C; and

an aperture 1) open to an atmosphere of the Earth or 2) covered with a transparent window, to pass the concentrated solar energy into the solar thermal receiver to impinge on the multiple reactor tubes and cavity walls of the receiver, wherein the reactor tubes serve the dual functions of 1) segregating the biomass gasification reaction environment from the atmosphere of the solar thermal receiver and 2) transferring solar energy by absorption and re-radiation, convection, and conduction to the reacting particles to drive the endothermic gasification reactions of the particles of biomass flowing through the reactor tubes, and wherein high heat transfer rates of the materials making up the cavity walls and the reactor tubes allow the particles biomass to achieve a high enough temperature necessary for substantial tar destruction to less than 200 mg/m^3 and preferably less than 50 mg/m^3 and gasification of greater than 90 percent of the carbon content of the particles into reaction products including hydrogen and carbon monoxide gas in a very short residence time between a range of 0.01 and 5 seconds.

2. The solar-driven chemical plant of claim 1, 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 chemical synthesis reactor has an input to receive the hydrogen and carbon monoxide products and use them in a hydrocarbon synthesis process to create a liquid hydrocarbon or other hydrocarbons including methanol; and

a top of the multiple reactor tubes, wherein the tubes are oriented vertically in the solar 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 1000 degrees C and 1600 degrees C and a gas temperature from an exit of the gasification reaction zone of the reactor tubes is in excess of 1000 degrees C but not above 1600 degrees C.

3. The solar-driven chemical plant of claim 1, wherein the reactor tubes inner diameter are sized to allow a substantially uniform gasification of the biomass particles from the edges to the center of the tube, and have a wall thickness set to withstand at least a 75 psig pressure at 1400 degrees C on the inside tube walls.

4. The solar-driven chemical plant of claim 1, wherein the one or more apertures are part of a receiver outer shell that at least partially encloses the multiple reactor tubes, wherein the receiver inner wall absorbs or highly reflects the concentrated solar energy from the array of heliostats to cause a radiant heat and then generally radiatively transmits that heat to the biomass particles in the tubes of

the solar driven chemical reactor, and an inner wall of the receiver cavity is made of material to allow the receiver cavity to be operated at high, >1200 degrees C, wall temperatures to enable the high heat transfer rates, rapid reaction kinetics of the very short residence time, and high selectivity of carbon monoxide and hydrogen produced from the gasification reaction for syngas, and

the reactor tubes are constructed of a transparent or semi transparent material including sapphire, allowing radiation to pass directly through the reactor tube and impinge on any reactive particles within the tubes.

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

an opaque outer wall for each of the reactor tubes;

an inner wall of the receiver, wherein the inner wall 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 even though the concentrated solar energy the heliostat array is merely directly impinging on the reactor tubes from one direction, and wherein the radiation heat transfer from the inner wall and the reactor tubes is the primary source of energy driving the gasification reaction in which the small biomass particles act as tiny absorbing surfaces of radiant heat energy coming from the inner wall and the tubes; and

wherein a shape of each reactor tube is a cylindrical shaped pipe, at least 30 reactor tubes are present in the cavity of the solar thermal receiver, the geometric arrangement of the multiple reactor tubes relative to each other is an arc pattern.

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

materials making up a wall of the receiver cavity have mechanical and chemical properties to withstand its strength at high temperatures between 1000-1600 degrees C, have very high

emissivity (ε>0.8) or high reflectivity (ε<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 including 0.7 emissivity coefficient or better, high thermal conductivity including 30 watts per meter-Kelvin or better, at least moderate heat capacity of 8 joules per mole–degree Kelvin or better, and is resistant to both the oxidizing air environment in the cavity of the receiver as well as the reducing environment on an interior of the tube in order to allow within the tubes the rapid gasification of dispersed falling biomass particulates with a resultant stable ash formation, amelioration of tar to less than 50 milligrams per normal cubic meter millimeter, and the production of the hydrogen and carbon monoxide products at operating temperatures within the tubes between 1000-1600 degrees C.

7. The solar-driven chemical plant of claim 6, wherein the inside walls of the receiver cavity are constructed of refractory alumina plate, outside of this refractory alumina plate layer is alumina fiber insulation, which is contained by a first structural carbon steel shell, where there is an air gap beyond this first carbon steel shell, followed by a second carbon steel shell, and wherein the thickness of the insulation, air gap and steel shells has been designed so as to limit conductive losses from the cavity to less than 5% of the concentrated solar energy incident from the heliostat array on the aperture of the solar thermal receiver.

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

a first and second reactor tubes of the multiple tubes, which are materially made of refractory ceramics or metals, wherein the material chosen must have good chemical stability and high strength at high temperatures between 1100-1600 degrees C, high corrosion

and abrasion resistance rates for the particle size of the biomass and steam concentration, good resistance to brittleness from solar flux, good thermal shock resistance resulting from rapid changes in available solar energy, high oxidation resistance at high temperatures if the receiver cavity is filled with a non-inert gas including air, good at absorbing solar energy, high re-radiating properties via radiation emissivity (ε>0.8), and high thermal conductivity (>1 W/m-K), and

wherein the material chosen for tube construction is selected from the group of materials, individually or in combination, including silicon-carbide, silicon-carbide coated graphite, Tungsten, molybdenum, mullite, zirconia, molybdenum with Aluminum Sulfide, Sintered submicron silicon carbide powder, transparent sapphire, high aluminum content nickel-base alloys, and refractory ceramics including aluminum oxide (Al203).

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

wherein the reactor tubes are made of coated graphite; and

wherein the window is made of sapphire and allows the cavity of the receiver to be enclosed, and an inert gas supply to cause the volume in the receiver cavity to be flooded with an inert gas excluding oxygen from affecting the reactor tubes made of coated graphite.

10. The solar-driven chemical plant of claim 8, wherein the high oxidation resistance at high temperatures can be provided by a coating of silicon carbide between 0.001" and 0.020" thick, placed on the reactor tube through chemical vapor deposition or through direct siliconization of the graphite and the reactor tubes will be operated at wall temperatures between 1000 degrees C and 1600 degrees C, and wherein a geometrical configuration of the multiple reactor tubes in the receiver relative to each other is in either a cylindrical or rectangular pattern.

11. The solar-driven chemical plant of claim 1, wherein a length and diameter dimensions of a gasification reaction zone of each of the reactor tubes is sized to give the very short residence time of 0.01 second to 5 second at the gasification temperatures, and a first of the multiple tubes has a larger diameter than a second of the multiple tubes, and the shape of each tube is either a cylindrical shaped pipe or a rectangular shaped pipe.

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

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, which allows balancing of 1) an 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; and

a computerized control system configured to balance the amount of biomass particles flowing in each of the reactor tubes to an amount of solar energy available.

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

an entrained-flow biomass feed system having a grinder to grind and pulverize biomass to a particle size controlled to an average smallest dimension size between 50 microns (um) and 2000 um, with a general range of between 200 um and 1000 um; and wherein the entrained-flow biomass feed system supplies a variety of biomass sources fed as particles into the solar driven chemical reactor without changing the reactor's structure, where the variety includes three or more types of biomass that can be fed, individually or in combinational mixtures, from the group consisting of rice straw, rice hulls, corn stover, switch grass, wheat straw, miscanthus,

orchard wastes, forestry wastes, energy crops, source separated green wastes and other similar biomass sources in a raw state or partially torrefied state, as long as a few parameters are controlled including particle size of the biomass and operating temperature range of the reactor tubes, and thus two or more different types of biomass materials can be used in the same reactor tube geometry and design; and

a feedforward and feedback control system configured to manage predicted changes in available solar energy as well as actual measured stochastic changes in available solar energy, wherein the control system balances the gasification reaction between biomass feed rate and an amount energy solar energy directed at the aperture of the receiver to keep a temperature at which the chemical reactor operates at 1) a high enough temperature for the greater than 90 percent conversion of the carbon content of the biomass to product gases including carbon monoxide and hydrogen as well as an elimination of tar products and 2) a low enough reactor tube wall temperature to not structurally weaken the walls or significantly reduce receiver efficiency.

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

an entrained-flow biomass feed system having one or more feed lines to feed the biomass particles into the multiple reaction 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, where each of the feed lines controls a dispersion pattern of the biomass particles into its corresponding reactor tube to maximize radiation absorption by the particles of biomass 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;

wherein the reactor tubes are constructed from a material to withstand temperatures up to 1600 degrees C and retain their structural strength, resistant to an oxidative environment on one side exposed to the receiver cavity via the addition of a coating, resistant to steam and a reducing environment on the other side in which the gasification reaction occurs, and pressure resistant up to 75 PSIG, and

a return tube that passes outside the receiver for the multiple reactor tubes to recycle all or a portion of the products of the gasification reaction from the exit of the chemical reactor.

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

insulation on an outside shell of the receiver to maintain heat during operations and overnight during shutdown, wherein the insulation is thick enough to keep conductive losses to less than 10% during operations and includes one or more from the group consisting of ceramic brick, ceramic blanket, or other refractory materials, or combinations of these;

a small boiler or resistance heaters connected to the outside shell of the receiver to aid in temperature control of the chemical reactor; and

multiple solar thermal receivers, wherein each receiver contains a chemical reactor and the multiple solar thermal receivers share a common tower.

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

an exit of a gasification reaction zone in the reactor tubes of the chemical reactor, at which the biomass gasification products from the multiple tubes are joined into several large tubes and then water or methanol is injected into the large tubes to rapidly cool the product gases and, in the case of water injection, provide steam for the water gas-shift reaction necessary to achieve a proper H2 to CO ratio

between 2.0 and 2.7 for syngas used by the on-site fuel synthesis reactor in the fuel synthesis process, and

wherein material for the multiple reactor tubes includes semi transparent sapphire, SiC coated graphite, Si/SiC composites, mullite, and ceramic matrix composites including melt infiltrated SiC/SiC, wherein the multiple reactor tubes have one or more of an added 1) abrasion resistant coating, 2) heat resistant coating >1050 degrees C, and 3) corrosion resistant coating, and wherein the coatings may be added onto the reactor tubes and receiver cavity inner surfaces in a number of ways including sputtering, and deposition.

17. A solar-driven chemical plant, comprising:

a solar thermal receiver aligned to absorb concentrated solar energy from an array of heliostats, a set of solar concentrators, or a combination of both, where the solar thermal receiver has cavity walls;

a solar driven chemical reactor that has multiple reactor tubes located inside the solar thermal receiver, where an endothermic chemical reaction occurs in the multiple reactor tubes to produce hydrogen and carbon monoxide products at an exit temperature from the tubes exceeding 1000 degrees C; wherein the reactor tubes are configured to the produce hydrogen and carbon monoxide products from one or more of the following reactants in the tubes: (i) biomass particles and steam (ii) biomass particles, methane, and steam, (iii) methane and steam (SMR), wherein different reactor tubes within the same receiver are constructed of a material to operate with the different chemical reactants; and

an aperture 1) covered by a transparent window or 2) open to the atmosphere, to pass the concentrated solar energy into the solar thermal receiver to impinge on the multiple reactor tubes and cavity walls of the receiver, wherein high heat transfer rates between the

materials making up the cavity walls and the reactor tubes allow the reactants to achieve a high enough temperature necessary for 1) in the case of biomass particles, substantial tar destruction and gasification of greater than 90 percent of the particles into reaction products including hydrogen and carbon monoxide gas in very short residence times between a range of 0.01 and 5 seconds or 2) in the case of gaseous reactants, greater than 90 percent of the equilibrium value for the chemical reaction occurring in the process in very short residence times between a range of 0.01 and 5 seconds.

18. The solar-driven biorefinery of claim 17, further comprising:

a heat transfer aid in the form of a structured packing used to heat the reactant gases, where the structured packing is one or more of the following reticulate porous ceramic (RPC) foam, a ceramic monolith, metallic wires, or ceramic tubes inside each reactor tube; and wherein the packing configured for radiation as the primary mode of heat transfer to the heat transfer aids from the reactor tube walls; and wherein conduction, convection, or some combination of the two are secondary modes of heat transfer; and

an on-site 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 or reforming reaction, wherein the on-site fuel synthesis reactor has an input to receive the hydrogen and carbon monoxide products and use them in a hydrocarbon synthesis process to create a liquid hydrocarbon fuels or chemicals.

19. The solar-driven biorefinery of claim 17, further comprising:

a heat transfer aid in the form of a particulate flow of inert particles used to heat the reactant gases, where the flow of inert particles is passed through the chemical reactor operating as a riser

in the case of an updraft circulating fluidized bed, or as a downer in the case of a downdraft circulating fluidized bed;

a fluidizing gas source from which a reactant gas entrains the inert particles, or inert particles and biomass particles, upward or downward through the reactor tubes; and

a return tube for the circulating fluidized bed that passes through or outside of the solar thermal receiver, and where the reactant gas flows counter-currently or co-currently with the downward traveling inert particles.

20. The solar-driven biorefinery of claim 17, further comprising:

a heat transfer aid in the form of a particulate flow of inert particles used to heat the reactant gases, where the flow of inert particles is mechanically metered and entrained in the gas flow and fed either upward or downward through the reactor tubes;

a separator coupled to the chemical reactor, wherein inert particles are mechanically separated from the product gas stream and recovered for reuse; and

wherein the heat transfer aid used to heat the reactant gases further comprises a non-circulating fluidized bed of inert particles and the reactant gas with the biomass and inert particles is the fluidizing gas and the fluidized portion of a reactant bed comprises a heated length of the reactor tube.

AMENDED CLAIMS
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Article 19 Amendment Replacement Claims

1. A chemical plant, comprising:

a thermal receiver having cavity walls;

a radiant heat driven chemical reactor that has multiple reactor tubes in a downdraft configuration located inside the thermal receiver, where in the multiple reactor tubes particles of biomass are gasified in the presence of a carrier gas in an endothermic gasification reaction to produce hydrogen and carbon monoxide products at an exit temperature from the tubes exceeding 1000 degrees C; and

wherein the reactor tubes serve the dual functions of 1) segregating the biomass gasification reaction environment from the atmosphere of the thermal receiver and 2) transferring energy by absorption and re-radiation, convection, and conduction to the reacting particles to drive the endothermic gasification reactions of the particles of biomass flowing through the reactor tubes, and wherein high heat transfer rates of the materials making up the cavity walls and the reactor tubes allow the particles biomass

to achieve a high enough temperature necessary for substantial tar destruction to less than 200 mg/m^3 and preferably less than 50 mg/m^3 and gasification of greater than 90 percent of the carbon content of the particles into reaction products including hydrogen and carbon monoxide gas in a very short residence time between a range of 0.01 and 5 seconds.

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 inside the solar thermal receiver or 2) covered with a transparent window, to pass the concentrated solar energy into the solar thermal receiver to impinge on the multiple reactor tubes and cavity walls of the receiver; and

a top of the multiple reactor tubes, wherein the tubes are oriented vertically in the solar 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 1000 degrees C and 1600 degrees C and a gas temperature from an exit of the

gasification reaction zone of the reactor tubes is in excess of 1000 degrees C but not above 1600 degrees C.

3. The chemical plant of claim 1, 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 chemical synthesis reactor has an input to receive the hydrogen and carbon monoxide products and use them in a hydrocarbon synthesis process to create a liquid hydrocarbon or hydrocarbons, wherein the reactor tubes inner diameter are sized to allow a substantially uniform gasification of the biomass particles from the edges to the center of the tube, and have a wall thickness set to withstand at least a 75 psig pressure at 1400 degrees C on the inside tube walls.

4. The chemical plant of claim 2, wherein the one or more apertures are part of a receiver outer shell that at least partially encloses the multiple reactor tubes, wherein the receiver inner wall absorbs or highly reflects the concentrated solar energy from the array of heliostats to cause a radiant heat and then generally radiatively transmits that heat to the biomass particles in the tubes of the solar driven chemical reactor, and an inner wall of the receiver cavity is made of material to allow the receiver cavity to be operated at high, >1200 degrees C, wall temperatures to enable the high heat transfer rates, rapid reaction kinetics of the very short residence time, and high selectivity of carbon monoxide and hydrogen produced from the gasification reaction for syngas, and

the reactor tubes are constructed of a transparent or semi transparent material including sapphire, allowing radiation to pass directly through the reactor tube and impinge on any reactive particles within the tubes.

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

an opaque outer wall for each of the reactor tubes;

an inner wall of the receiver, wherein the inner wall 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 even though the concentrated solar energy the heliostat array is merely directly impinging on the reactor tubes from one direction, and wherein the radiation heat transfer from the inner wall and the reactor tubes is the primary source of energy driving the gasification reaction in which the small biomass particles act as tiny absorbing surfaces of radiant heat energy coming from the inner wall and the tubes; and

wherein a shape of each reactor tube is a cylindrical shaped pipe, at least 30 reactor tubes are present in the cavity of the solar thermal receiver, the geometric arrangement of the multiple reactor tubes relative to each other is an arc pattern.

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

materials making up a wall of the receiver cavity have mechanical and chemical properties to withstand its strength at high temperatures between 1000-1600 degrees C, have very high emissivity ($\varepsilon>0.8$) or high reflectivity ($\varepsilon<0.2$) 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 including 0.7 emissivity coefficient or better, high thermal conductivity including 30 watts per meter-Kelvin or better, at least moderate heat capacity of 8 joules per mole–degree Kelvin or better, and is resistant to both the oxidizing air environment in the cavity of the receiver as well as the reducing environment on an interior of the tube in order to allow within the tubes the rapid gasification of dispersed falling biomass particulates with a resultant stable ash formation, amelioration of tar to less than 50 milligrams per normal cubic meter millimeter, and the production of the hydrogen and carbon monoxide products at operating temperatures within the tubes between 1000-1600 degrees C.

7. The chemical plant of claim 6, wherein the inside walls of the receiver cavity are constructed of refractory alumina plate, outside of this refractory alumina plate layer is alumina fiber insulation, which is contained by a first structural carbon steel shell, where there is an air gap beyond this first carbon steel shell, followed by a second carbon steel shell, and wherein the thickness of the insulation, air gap and steel shells has been designed so as to limit conductive losses from the cavity to less than 5% of the concentrated solar energy incident from the heliostat array on the aperture of the solar thermal receiver.

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

a first and second reactor tubes of the multiple tubes, which are materially made of refractory ceramics or metals, wherein the material chosen must have good chemical stability and high strength at high temperatures between 1100-1600 degrees C, high

corrosion and abrasion resistance rates for the particle size of the biomass and steam concentration, high oxidation resistance at high temperatures if the receiver cavity is filled with a non-inert gas including air, high re-radiating properties via radiation emissivity (ε>0.8), and high thermal conductivity (>1 W/m-K), and

wherein the material chosen for tube construction is selected from the group of materials, individually or in combination, including silicon-carbide, silicon-carbide coated graphite, Tungsten, molybdenum, mullite, zirconia, molybdenum with Aluminum Sulfide, Sintered submicron silicon carbide powder, transparent sapphire, high aluminum content nickel-base alloys, and refractory ceramics including aluminum oxide (Al203).

9. The chemical plant of claim 8, further comprising:

wherein the reactor tubes are made of coated graphite; and

wherein the window is made of sapphire and allows the cavity of the receiver to be enclosed, and an inert gas supply to cause the volume in the receiver cavity to be flooded with an inert gas excluding oxygen from affecting the reactor tubes made of coated graphite.

10. The chemical plant of claim 8, wherein the high oxidation resistance at high temperatures can be provided by a coating of silicon carbide between 0.001" and 0.020" thick, placed on the reactor tube through chemical vapor deposition or through direct siliconization of the graphite and the reactor tubes will be operated at wall temperatures between 1000 degrees C and 1600 degrees C, and wherein a geometrical configuration

of the multiple reactor tubes in the receiver relative to each other is in either a cylindrical or rectangular pattern.

11. The chemical plant of claim 1, wherein a length and diameter dimensions of a gasification reaction zone of each of the reactor tubes is sized to give the very short residence time of 0.01 second to 5 second at the gasification temperatures, and a first of the multiple tubes has a larger diameter than a second of the multiple tubes, and the shape of each tube is either a cylindrical shaped pipe or a rectangular shaped pipe.

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

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, which allows balancing of 1) an 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; and

a computerized control system configured to balance the amount of biomass particles flowing in each of the reactor tubes to an amount of solar energy available.

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

an entrained-flow biomass feed system having a grinder to grind and pulverize biomass to a particle size controlled to an average smallest dimension size between 50

microns (um) and 2000 um, with a general range of between 200 um and 1000 um; and wherein the entrained-flow biomass feed system supplies a variety of biomass sources fed as particles into the solar driven chemical reactor without changing the reactor's structure, where the variety includes three or more types of biomass that can be fed, individually or in combinational mixtures, from the group consisting of rice straw, rice hulls, corn stover, switch grass, wheat straw, miscanthus, orchard wastes, forestry wastes, energy crops, source separated green wastes and other similar biomass sources in a raw state or partially torrefied state, as long as a few parameters are controlled including particle size of the biomass and operating temperature range of the reactor tubes, and thus two or more different types of biomass materials can be used in the same reactor tube geometry and design; and

a feedforward and feedback control system configured to manage predicted changes in available solar energy as well as actual measured stochastic changes in available solar energy, wherein the control system balances the gasification reaction between biomass feed rate and an amount energy solar energy directed at the aperture of the receiver to keep a temperature at which the chemical reactor operates at 1) a high enough temperature for the greater than 90 percent conversion of the carbon content of the biomass to product gases including carbon monoxide and hydrogen as well as an elimination of tar products and 2) a low enough reactor tube wall temperature to not structurally weaken the walls or significantly reduce receiver efficiency.

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

an entrained-flow biomass feed system having one or more feed lines to feed the biomass particles into the multiple reaction 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, where each of the feed lines controls a dispersion pattern of the biomass particles into its corresponding reactor tube to maximize radiation absorption by the particles of biomass 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;

wherein the reactor tubes are constructed from a material to withstand temperatures up to 1600 degrees C and retain their structural strength, resistant to an oxidative environment on one side exposed to the receiver cavity via the addition of a coating, resistant to steam and a reducing environment on the other side in which the gasification reaction occurs, and pressure resistant up to 75 PSIG, and

a return tube that passes outside the receiver for the multiple reactor tubes to recycle all or a portion of the products of the gasification reaction from the exit of the chemical reactor.

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

insulation on an outside shell of the receiver to maintain heat during operations and overnight during shutdown, wherein the insulation is thick enough to keep conductive losses to less than 10% during operations and includes one or more from the group consisting of ceramic brick, ceramic blanket, or other refractory materials, or combinations of these;

a small boiler or resistance heaters connected to the outside shell of the receiver to aid in temperature control of the chemical reactor; and

multiple solar thermal receivers, wherein each receiver contains a chemical reactor and the multiple solar thermal receivers share a common tower.

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

an exit of a gasification reaction zone in the reactor tubes of the chemical reactor, at which the biomass gasification products from the multiple tubes are joined into several large tubes and then water or methanol is injected into the large tubes to rapidly cool the product gases and, in the case of water injection, provide steam for the water gas-shift reaction necessary to achieve a proper H2 to CO ratio between 2.0 and 2.7 for syngas used by the on-site fuel synthesis reactor in the fuel synthesis process, and

wherein material for the multiple reactor tubes includes semi transparent sapphire, SiC coated graphite, Si/SiC composites, mullite, and ceramic matrix composites including melt infiltrated SiC/SiC, wherein the multiple reactor tubes have one or more of an added 1) abrasion resistant coating, 2) heat resistant coating >1050 degrees C, and 3) corrosion resistant coating, and wherein the coatings may be added onto the reactor tubes and receiver cavity inner surfaces in a number of ways including sputtering, and deposition.

17. A bio-refinery, comprising:

a thermal receiver having cavity walls;

a radiant heat driven chemical reactor that has multiple reactor tubes located inside the thermal receiver, where an endothermic chemical reaction occurs in the multiple reactor tubes to produce hydrogen and carbon monoxide products at an exit temperature from the tubes exceeding 1000 degrees C; wherein the reactor tubes are configured to the produce hydrogen and carbon monoxide products from one or more of the following reactants in the tubes: (i) biomass particles and steam (ii) biomass particles, methane, and steam, (iii) methane and steam (SMR), wherein different reactor tubes within the same receiver are constructed of a material to operate with the different chemical reactants; and

wherein high heat transfer rates between the materials making up the cavity walls and the reactor tubes allow the reactants to achieve a high enough temperature necessary for 1) in the case of biomass particles, substantial tar destruction and gasification of greater than 90 percent of the particles into reaction products including hydrogen and carbon monoxide gas in very short residence times between a range of 0.01 and 5 seconds or 2) in the case of gaseous reactants, greater than 90 percent of the equilibrium value for the chemical reaction occurring in the process in very short residence times between a range of 0.01 and 5 seconds.

18. The bio-refinery of claim 17, further comprising:

a heat transfer aid in the form of a structured packing used to heat the reactant gases, where the structured packing is one or more of the following reticulate porous ceramic (RPC) foam, a ceramic monolith, metallic wires, or ceramic tubes inside each reactor tube; and wherein the packing configured for radiation as the primary mode of

heat transfer to the heat transfer aids from the reactor tube walls; and wherein conduction, convection, or some combination of the two are secondary modes of heat transfer; and

an on-site 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 or reforming reaction, wherein the on-site fuel synthesis reactor has an input to receive the hydrogen and carbon monoxide products and use them in a hydrocarbon synthesis process to create a liquid hydrocarbon fuels or chemicals.

19. The biorefinery of claim 17, further comprising:

a heat transfer aid in the form of a particulate flow of inert particles used to heat the reactant gases, where the flow of inert particles is passed through the chemical reactor operating as a riser in the case of an updraft circulating fluidized bed, or as a downer in the case of a downdraft circulating fluidized bed;

a fluidizing gas source from which a reactant gas entrains the inert particles, or inert particles and biomass particles, upward or downward through the reactor tubes; and

a return tube for the circulating fluidized bed that passes through or outside of the thermal receiver, and where the reactant gas flows counter-currently or co-currently with the downward traveling inert particles.

20. The biorefinery of claim 17, further comprising:

wherein the 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 and thus a solar-driven chemical reactor that has multiple reactor tubes;

an aperture 1) open to an atmosphere inside the solar thermal receiver or 2) covered with a transparent window, to pass the concentrated solar energy into the solar thermal receiver to impinge on the multiple reactor tubes and cavity walls of the receiver;

a heat transfer aid in the form of a particulate flow of inert particles used to heat the reactant gases, where the flow of inert particles is mechanically metered and entrained in the gas flow and fed either upward or downward through the reactor tubes;

a separator coupled to the chemical reactor, wherein inert particles are mechanically separated from the product gas stream and recovered for reuse; and

wherein the heat transfer aid used to heat the reactant gases further comprises a non-circulating fluidized bed of inert particles and the reactant gas with the biomass and inert particles is the fluidizing gas and the fluidized portion of a reactant bed comprises a heated length of the reactor tube.

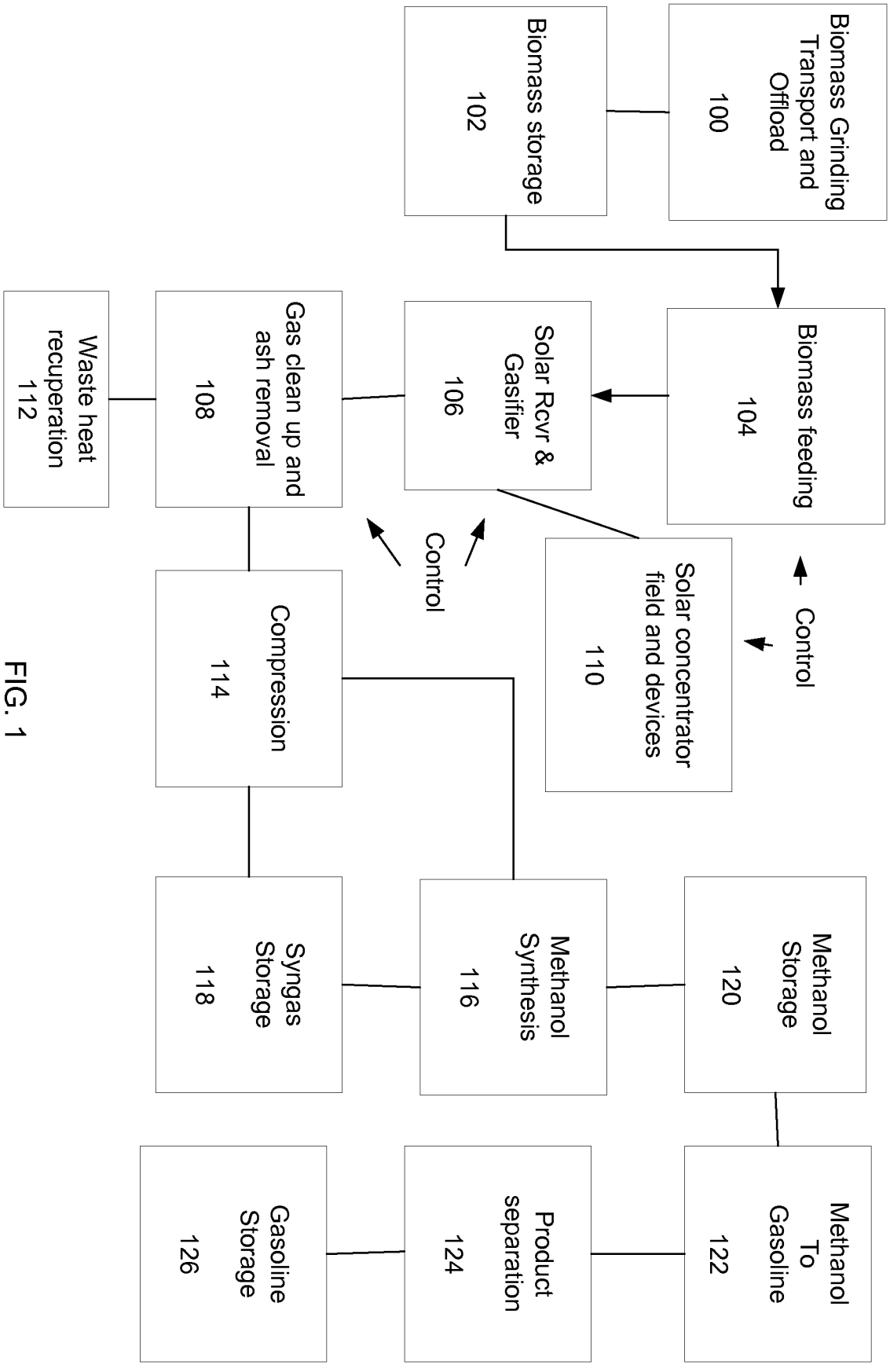

Biomass Grinding Transport and Offload
100
Biomass storage
102
Biomass feeding
104
Solar Rcvr & Gasifier
106
Gas clean up and ash removal
108
Waste heat recuperation
112
Solar concentrator field and devices
110
Control
Control
Compression
114
Syngas Storage
118
Methanol Synthesis
116
Methanol Storage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

FIG. 1

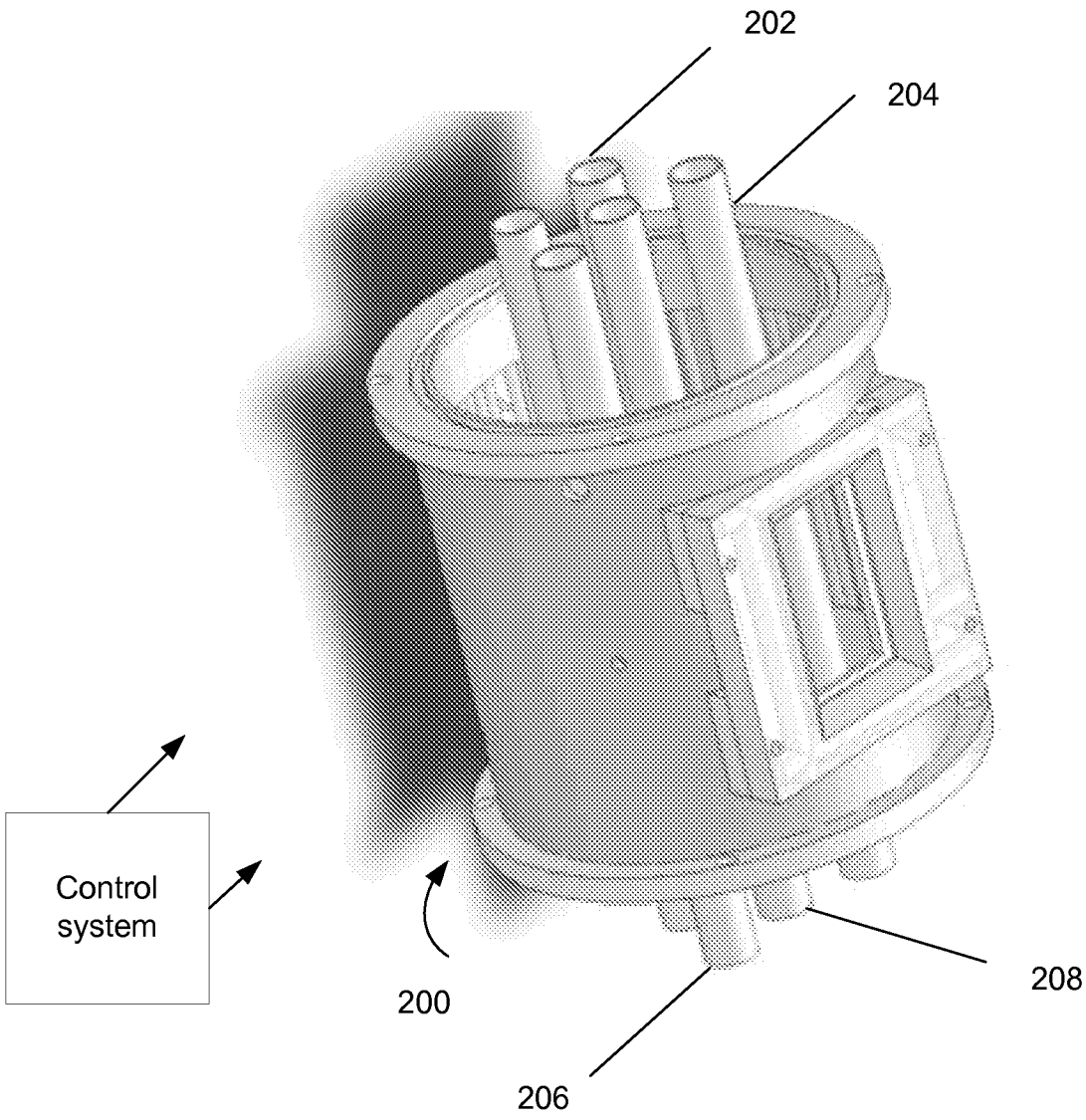


FIG. 2

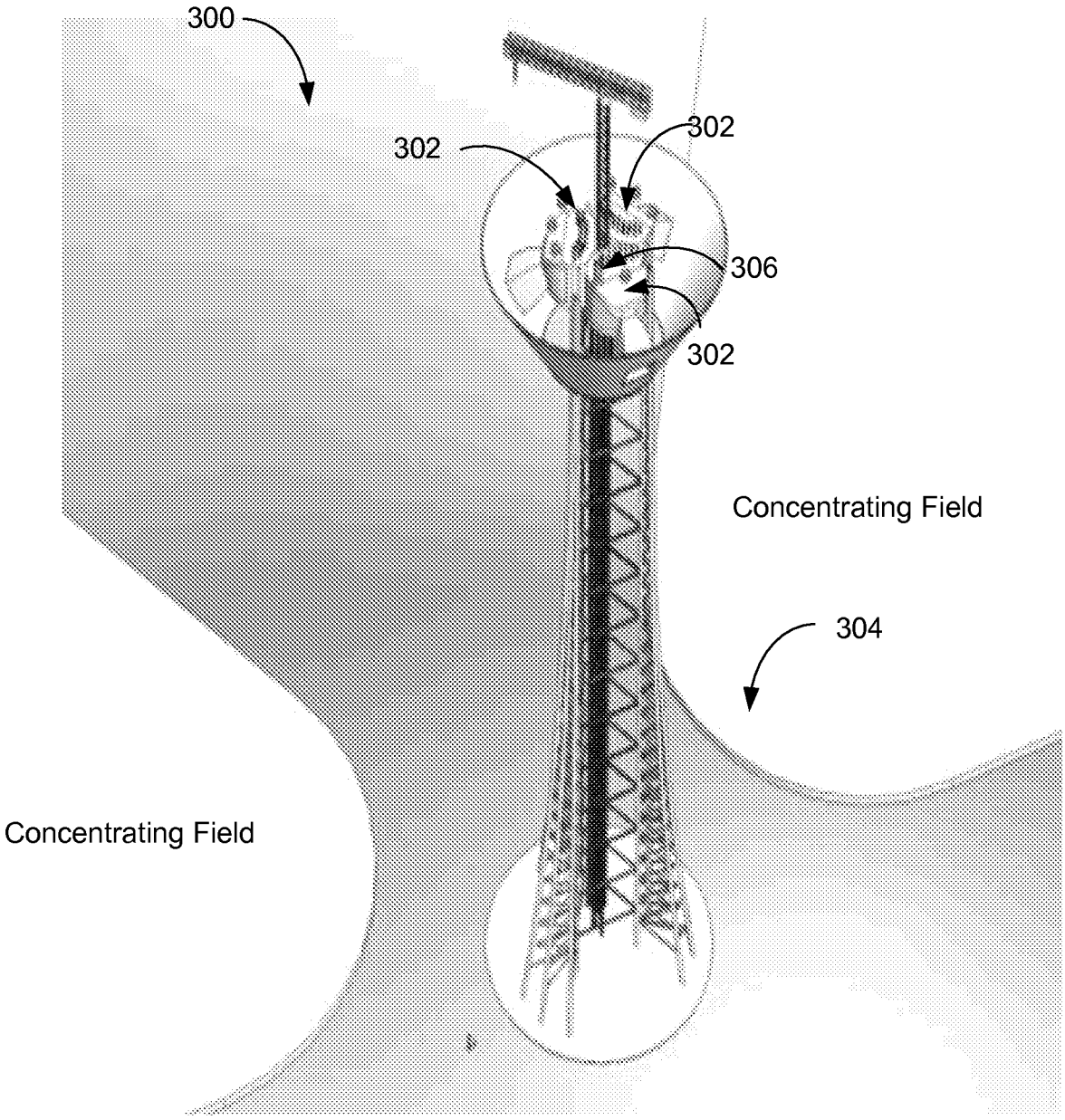

300
302
302
306
302
Concentrating Field
304
Concentrating Field

FIG. 3

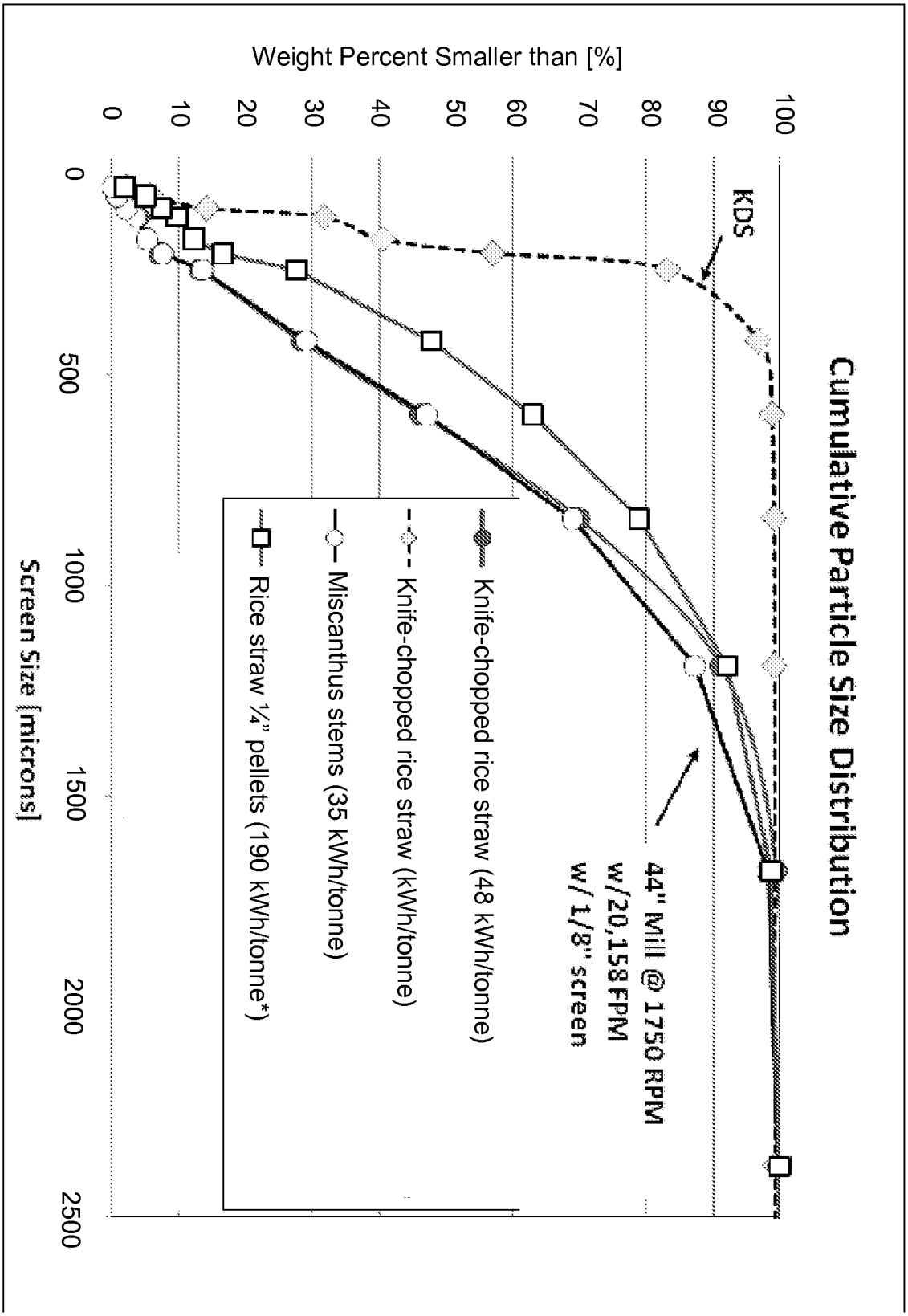

Cumulative Particle Size Distribution
Weight Percent Smaller than [%]
Screen Size [microns]
0
10
20
30
40
50
60
70
80
90
100
0
500
1000
1500
2000
2500
KDS
44" Mill @ 1750 RPM
w/20,158 FPM
w/ 1/8" screen
Knife-chopped rice straw (48 kWh/tonne)
Knife-chopped rice straw (kWh/tonne)
Miscanthus stems (35 kWh/tonne)
Rice straw ¼" pellets (190 kWh/tonne*)

FIG. 4

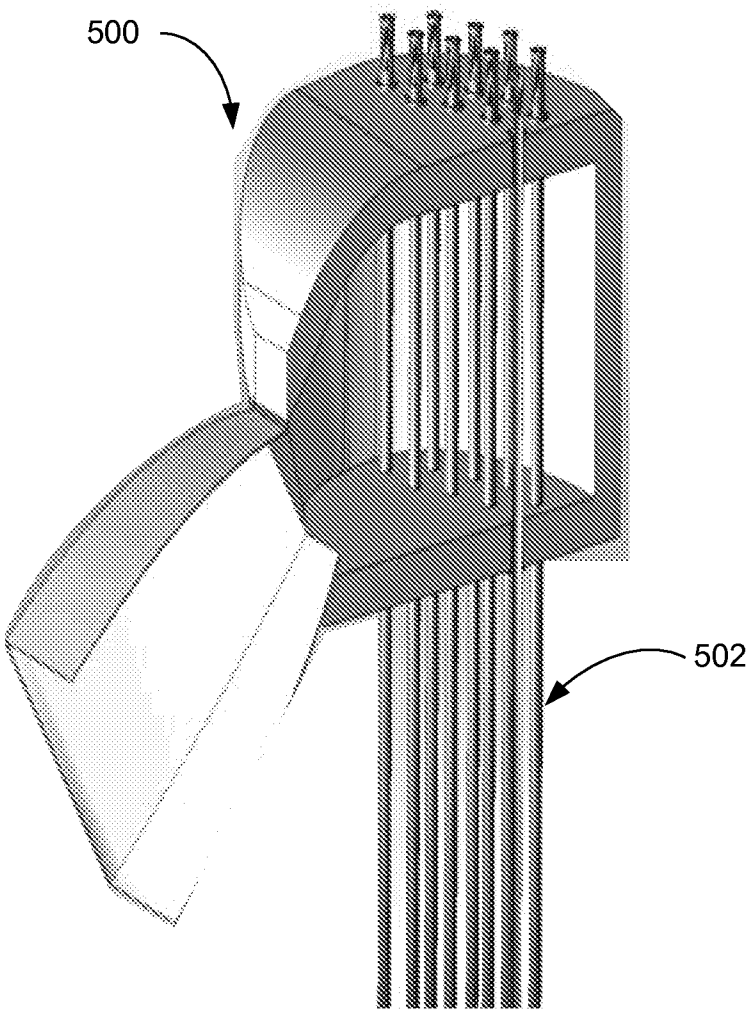


FIG. 5

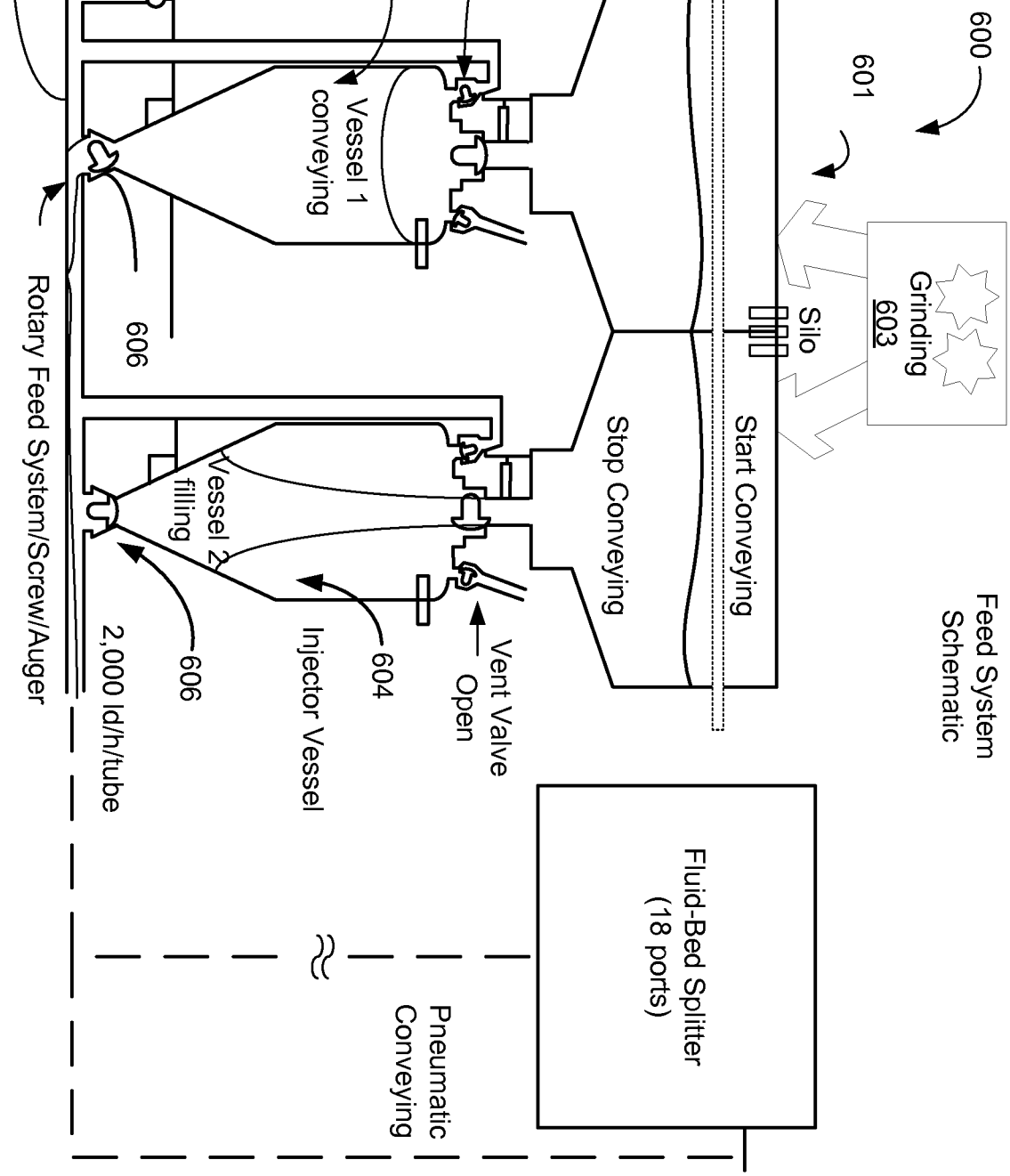

Feed System Schematic
600
601
Grinding 603
Silo
Start Conveying
Stop Conveying
Balance Valve Open
Continuous Entrainment Gas Supply 610
602
604
Vessel 1 conveying
606
Rotary Feed System/Screw/Auger
Vessel 2 filling
606
2,000 ld/h/tube
Injector Vessel
604
Vent Valve Open
Fluid-Bed Splitter (18 ports)
Pneumatic Conveying
Individual Gasifier Tubes

FIG. 6a

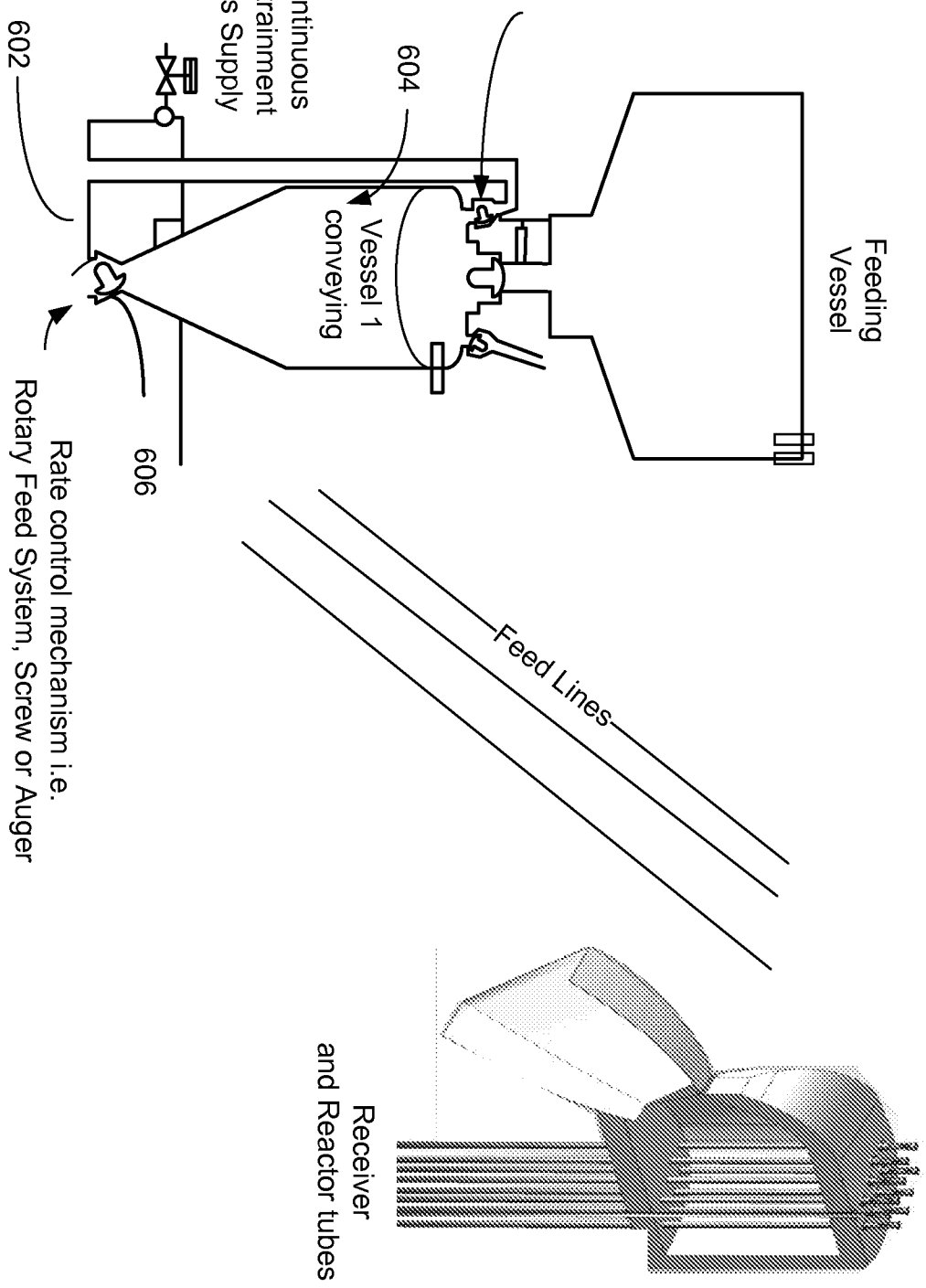

Feeding Vessel
Vessel 1 conveying
604
Continuous Entrainment Gas Supply
602
606
Rate control mechanism i.e. Rotary Feed System, Screw or Auger
Feed Lines
Receiver and Reactor tubes

Figure 6b

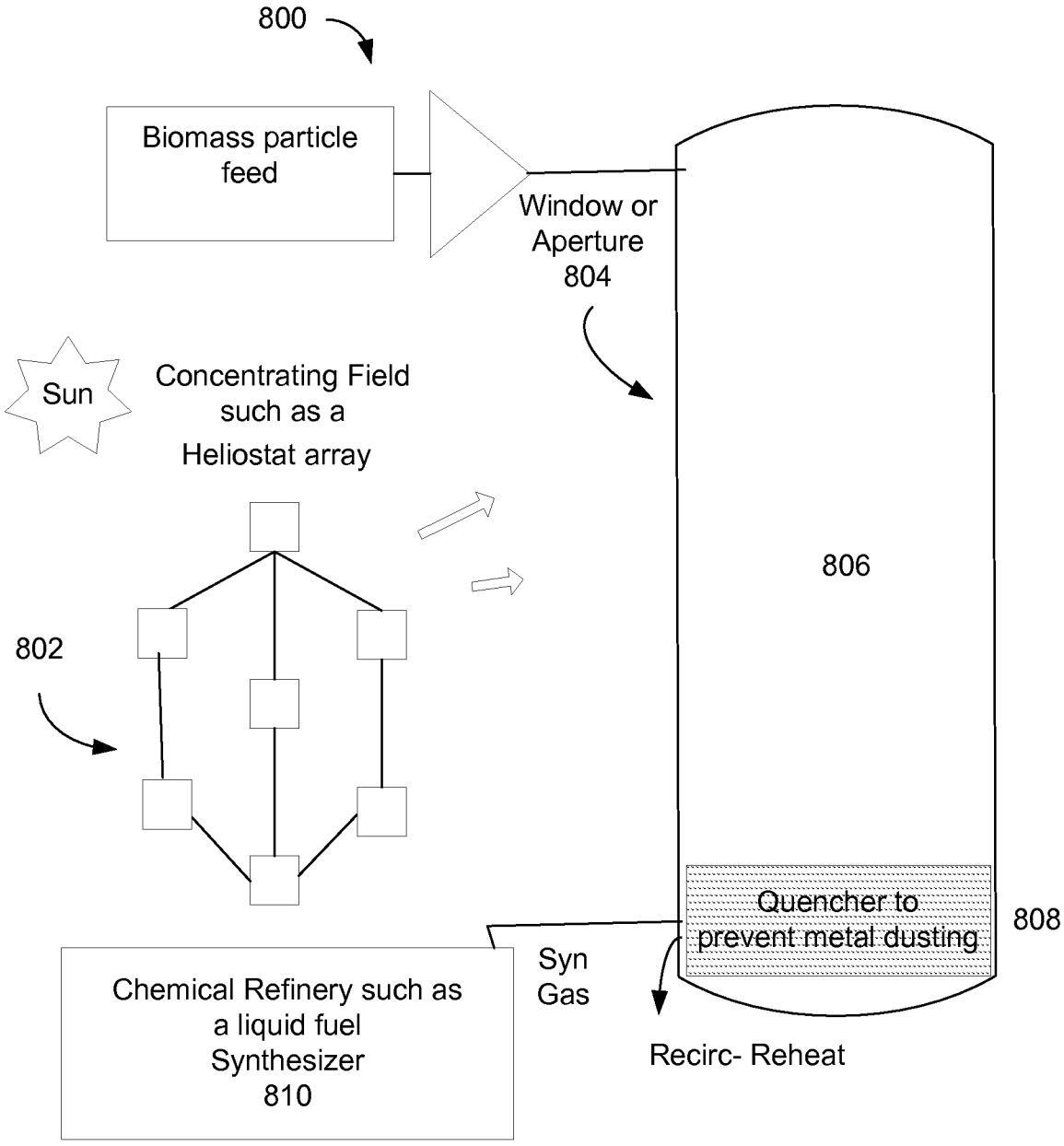

800
Biomass particle feed
Window or Aperture 804
Sun
Concentrating Field such as a Heliostat array
802
806
Quencher to prevent metal dusting
808
Syn Gas
Recirc- Reheat
Chemical Refinery such as a liquid fuel Synthesizer 810

FIG. 7

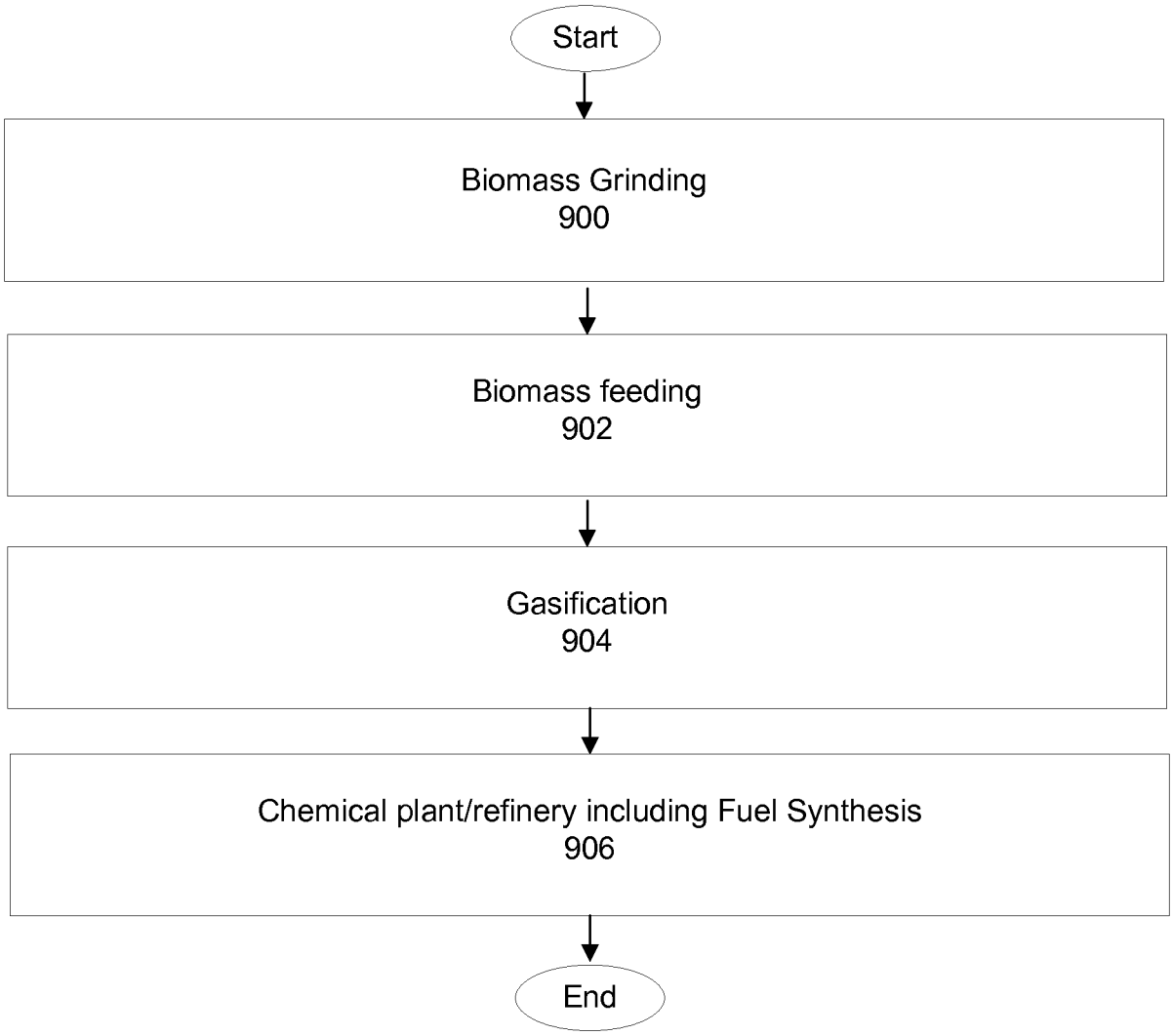

Start
Biomass Grinding
900
Biomass feeding
902
Gasification
904
Chemical plant/refinery including Fuel Synthesis
906
End

FIG. 8

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US 10/37938

A. CLASSIFICATION OF SUBJECT MATTER
IPC(8) - C10J 3/48 (2010.01)
USPC - 422/186; 48/89
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): C10J 3/48 (2010.01); USPC: 422/186; 48/89

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
USPC: 422/186; 48/89

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
Google Patents, Google Scholar, PubWEST (PGPB,USPT,EPAB,JPAB) (biomass, gasification, reactor, solar, thermal, heliostat, dish, tube, endothermic, hydrogen, carbon monoxide, aperture, segregate, separate, absorption, conduction, convection, radiation, tar, residence time, inert, gas, graphite, alumina, insulation)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X Y	US 2008/0086946 A1 (Weimer, et al.) 17 Apr 2008 (17.04.2008) Figure 2A, paragraphs 0009-0011, 0020, 0028-0034, 0038-0045, 0052-0071, 0079, 0086-0099, 0106-0111, 0122, 0126, 0130-0132	17 1-16, 18-20
Y	US 2007/0098602 A1 (Haueter, et al.) 03 May 2007 (03.05.2007) Figures 1, 1b, paragraphs 0009, 0030, 0034-0036, 0050-0056, 0060-0067, 0082	1-16
Y	US 2004/0219079 A1 (Hagen, et al.) 04 Nov 2004 (04.11.2004) Figures 1, 11, paragraphs 0361, 0486-0488, 0502, 0659, 0688, 0822, 0961, 1127, 1146-1156, 1176, 1189, 1193-1195, 1208, 1221, 1245, 1343-1345, 1383, 1565-1567	4, 9, 12, 14-16, 19-20
Y	US 5,906,799 A (Burgie, et al.) 25 May 1999 (25.05.1999) column 3, line 52-55, column 4, line 12-15	10
Y	US 7,207,327 B2 (Litwin, et al.) 24 Apr 2007 (24.04.2007) column 3, line 22-28, line 49-53, line 64-67, column 4, line 1-2	13
Y	US 5,618,500 A (Wang) 08 Apr 1997 (08.04.1997) column 3, line 19-22, line 30-33, column 4, line 9-16	18

☐ 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
23 Jul 2010 (23.07.2010)	05 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)