(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) **World Intellectual Property Organization**
International Bureau

(43) **International Publication Date**
16 December 2010 (16.12.2010)

PCT

(10) **International Publication Number**
WO 2010/144549 A1

(51) **International Patent Classification**:
B01J 19/08 (2006.01)

(21) **International Application Number**:
PCT/US2010/037934

(22) **International Filing Date**:
9 June 2010 (09.06.2010)

(25) **Filing Language**: English

(26) **Publication Language**: English

(30) **Priority Data**:
61/185,492 9 June 2009 (09.06.2009) US
61/248,282 2 October 2009 (02.10.2009) US
12/796,471 8 June 2010 (08.06.2010) US

(71) **Applicant** *(for all designated States except US)*: **SUNDROP FUELS, INC.** [US/US]; 1722 Boxelder Street, Louisville, CO 80027 (US).

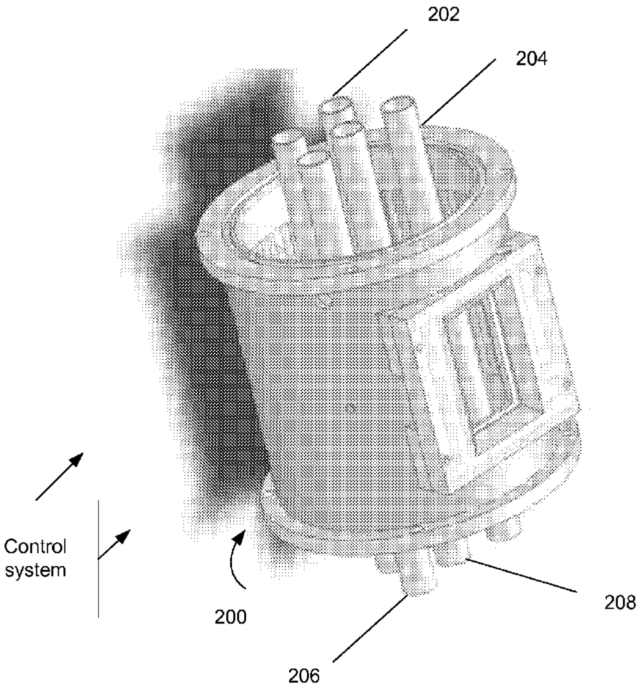
(72) **Inventors**: **PERKINS, Christopher**; 4271 Milliken Court, Boulder, Colorado 80303 (US). **JOVANOVIC, Zoran**; 1053 W. Century Drive, #202, Louisville, Colorado 80027 (US). **HILTON, Courtland**; 4795 W. 127th Place, Broomfield, Colorado 80020 (US). **LANCASTER, Brittany**; 2301 Pearl Street #67, Boulder, CO 80302 (US). **MINDEN, Andrew**; 2345 Spotswood Place, Boulder, Colorado 80304 (US). **RIDLEY, Richard**; 3289 Crowley Circle, Loveland, Colorado 80538 (US). **KELLEY, Donna**; 248 South McCaslin Boulevard, Louisville, Colorado 80027 (US).

(74) **Agent**: **FERRILL, Thomas S.**; Rutan & Tucker LLP, 611 Anton Boulevard, Suite 1400, Costa Mesa, CA 92626 (US).

(81) **Designated States** *(unless otherwise indicated, for every kind of national protection available)*: AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IS, JP, KE, KG, KM, KN, KP, KR, KZ, LA, LC, LK, LR, LS, LT, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI,

[Continued on next page]

(54) Title: SYSTEMS AND METHODS FOR REACTOR CHEMISTRY AND CONTROL



Multiple tube reactor

FIG. 2

(57) **Abstract**: A method, apparatus, and system for a solar-driven chemical plant that manages variations in solar energy are disclosed. Some embodiments include a solar thermal receiver to absorb concentrated solar energy, a solar driven chemical reactor contained within the solar thermal receiver, and an entrained gas biomass feed system that uses an entrainment carrier gas and supplies a variety of biomass sources fed as particles into the solar driven chemical reactor. Inner walls of the solar thermal receiver and the chemical reactor can be made from materials selected to transfer energy. Some embodiments include a control system that may be configured to balance the gasification reaction of biomass particles with the available concentrated solar energy and additional variable parameters including, but not limited to, a fixed range of particle sizes, temperature of the chemical reactor, and residence time of the particles in a reaction zone in the chemical reactor.

WO 2010/144549 A1

NO, NZ, OM, PE, PG, PH, PL, PT, RO, RS, RU, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

(84) Designated States *(unless otherwise indicated, for every kind of regional protection available)*: ARIPO (BW, GH, GM, KE, LR, LS, MW, MZ, NA, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

Published:

- *with international search report (Art. 21(3))*
- *with amended claims (Art. 19(1))*

SYSTEMS AND METHODS FOR REACTOR CHEMISTRY AND CONTROL

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.

NOTICE OF COPYRIGHT

[002] A portion of the disclosure of this patent document contains material that is subject to copyright protection. The copyright owner has no objection to the facsimile reproduction by anyone of the software engine and its modules, as it appears in the Patent and Trademark Office Patent file or records, but otherwise reserves all copyright rights whatsoever.

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. Energy must be put into the endothermic 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. 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 the energy source being used to drive the conversion is renewable and carbon free. Also, chemical reactors are generally engineered to operate at constant conditions around the clock, rather than on a cyclic basis.

SUMMARY OF THE INVENTION

[005] A method, apparatus, and system for a solar-driven chemical plant that manages variations in solar energy are disclosed. Some embodiments include a solar thermal receiver to aligned absorb concentrated solar energy from one or more solar energy concentrating fields including an array of heliostats, solar concentrating dishes, and any combination of the two. A solar driven chemical reactor may be at least partially contained within the solar thermal receiver. Some embodiments include an entrained gas biomass feed system that uses an entrainment carrier gas and supplies a variety of biomass sources fed as particles into the solar driven chemical reactor.

[006] Additionally, some embodiments include a control system. The control system may be configured to balance the gasification reaction of biomass particles with the available concentrated solar energy and additional variable parameters of a fixed range of particle size, temperature of the chemical reactor, and residence time of the particles in a reaction zone in the chemical reactor. This can allow for an overall biomass particle conversion remains above a threshold set point of substantial tar destruction to less than 50 mg/Nm^3 and complete gasification of greater than 90 percent of the carbon content of the particles into reaction products that include hydrogen and carbon monoxide gas.

[007] A feedforward portion and a feedback portion of the control system can be used to adapt for both long and short term disturbances in available solar energy. Additionally, the feedforward portion may anticipate cyclic changes in solar energy due to at least a time of day, day of the calendar it is, and periodic weather reports with a predictive model that adapts to the anticipated cyclic changes. The feedback portion may measure actual process parameters including the temperature of the chemical reactor at an entrance and an exit.

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 solar energy concentrating fields;

figure 4 illustrates a graph of an embodiment of particle size distribution of some example biomass types;

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 chemical plant; and

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

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

[009] 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 and features in one embodiment may be used in another embodiment. The specific details may be varied from and still be contemplated to be within the spirit and scope of the present invention. The term coupled is defined as meaning connected either directly to the component or indirectly to the component through another component.

[0010] In general, a method, apparatus, and system are described for a solar-driven chemical plant that manages variations in solar energy. An embodiment may include the solar thermal receiver, a solar driven chemical reactor at least partially contained within the solar thermal receiver, an entrained gas biomass feed system, and other components. The entrained gas biomass feed system may use an entrainment carrier gas to supply a variety of biomass sources fed as particles into the solar driven chemical reactor. Some embodiments include a control system that may be configured to balance the gasification reaction of biomass particles with the available concentrated solar energy and additional variable parameters of a fixed range of particle size, temperature of the chemical reactor, and residence time of the particles in a reaction zone in the chemical reactor.

[0011] The control system may also send a feed demand signal to the feed system. This can control a feed rate of the particles of biomass in the solar driven chemical reactor by changing a gas pressure and/or volumetric flow rate of the entrainment carrier gas. In some embodiments, control the feed rate may be done in combination with a metering device that controls a weight of biomass particles from a lock hopper to the feed lines that feed the chemical reactor.

[0012] The feedforward portion and a feedback portion of the control system in cooperation with designing in enough surface area, thermal mass, and heat capacity in the multiple tubes and receiver cavity is used to ensure that temperature of the reactor cavity remains in the operational temperature range of below 1600 degrees C and above 800 degrees C. This range may be maintained during potentially rapidly changing daily weather conditions. Additionally, a feed forward model may predict an available solar energy over each time period in a given day as well as each day throughout the year. The feedback portion may receive dynamic feedback from the temperature and/or light sensors. These may be combined to maintain both the quality and output of resultant syngas at above the threshold set point of substantial tar destruction to less than 50 mg/m^3 and complete gasification of greater than 90 percent of the carbon content of the biomass particles into the reaction products.

[0013] Figure 1 illustrates a block diagram of an example process flow. Some embodiments encompass a solar-driven-biomass gasification to liquid fuel/electrical process. The process might also include generation, chemical processing, or bio-char, for solar generated syngas derivative product or other similar technical process. In a specific example implementation the process described is a solar-driven-biomass gasification to ‘green’ liquid fuel process. In an embodiment, this process includes one or more of the following process steps.

[0014] Biomass grinding or densification, transport and offload 100 may be part of the overall process. Bales of the biomass can be compressed and densified by a compactor to facilitate transport to on-site via the densification achieved by the double compression. The bales are sized to dimensions that may, for example, fit within a standard box car size or fit within standard compactor size. The entrained-flow biomass feed system can be preceded by a grinding system equipped with mechanical cutting device and a particle classifier, such as a perforated screen or a cyclone, to control the size of the particles that are. The grinding system that has a mechanical cutting device such as a screw and set of filters with micron sized holes/screen diameter sized holes to control particle size. The mechanical screw and set of filters cooperate to grind and pulverize the stock biomass to particles to the micron sized holes of the filters, and the particles of biomass are then fed into and gasified in the solar-driven chemical reactor. The biomass may be in an embodiment non-food stock biomass. In other cases, food stock biomass or a combination of the two might also be processed.

[0015] The biomass may be stored 102. As needed, the biomass might be feed 104 into an example system or apparatus of the instant application. For example, after grinding and pulverizing the biomass to particles, the particles of biomass can be fed into and gasified in the solar-driven chemical reactor. Two or more feed line supply the particles of biomass having an average smallest dimension size between 50 microns (um) and 2000 um to the chemical reactor. An entrained gas biomass feed system uses an entrainment carrier gas to move a variety of biomass sources fed as particles into the solar driven chemical reactor.

[0016] A solar receiver and gasifier 106 may be used to break down the biomass. An example biomass gasifier design and operation can include a solar chemical reactor and solar receiver to generate components of syngas. The feedforward portion and the feedback portion of the control system adapt the operation of the reactor to both long and short term disturbances in available solar energy. Various solar concentrator field designs and operations to drive the biomass gasifier might be used. Some example systems may include a solar concentrator, focused mirror array, etc. to drive biomass gasifier 110.

[0017] 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.

[0018] An on-site fuel synthesis reactor that is geographically located on the same site as the chemical reactor and integrated to receive the hydrogen and carbon monoxide products from the gasification reaction can be used in some embodiments. Additionally, the on-site fuel synthesis reactor has an input to receive the hydrogen and carbon monoxide products and use them in a hydrocarbon fuel synthesis process to create a liquid hydrocarbon fuel. The on-site fuel synthesis reactor may be connected to the rest of the plant facility by a pipeline that is generally less than 15 miles in distance. The on-site fuel synthesis reactor may supply various feedback parameters and other request to the control system. For example, the on-site fuel synthesis reactor can request the control system to alter the H2 to CO ratio of the syngas coming out of the quenching and gas clean up portion of the plant and the control system will do so.

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

[0020] Figure 2 illustrates a diagram of an example multiple tube chemical reactor that may be used in a solar driven system. The chemical reactor has multiple reactor tubes 202, 204, 206, 208. 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 solar driven chemical reactor 200. The particles of biomass feed can be distributed to the reactor tubes 202, 204, 206, 208 by a lock hopper rotary feed system, such as a Rotofeed® lock hopper rotary feed system. Such a system can allow for balanced feeding to individual reactor tubes 202, 204, 206, 208 and feed rate of the particles is controlled by a weight measuring metering device such as load cells.

[0021] The biomass gasifier reactor and receiver control system may manage variations in solar energy by passing signal between itself and a solar energy concentrating field. Focused concentrated solar energy on the solar thermal receiver 200 may come 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.

[0022] The solar driven chemical reactor can be contained within the solar thermal receiver 200. The inner walls of the solar thermal receiver 200 and the chemical reactor may be made from materials selected to transfer energy by primarily heat radiation, along with convection, and conduction to the reacting biomass particles to drive the endothermic gasification reaction of the particles of biomass flowing through the chemical reactor.

[0023] 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. Likewise, different chemical reactions may take place in the same reactor tubes of the solar-driven chemical reactor at the same time. Also, the control system may control the chemical reactions occurring within the reactor tubes via a number of 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.

[0024] 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 steam methane reforming reaction occurring while a second set of tubes has a biomass gasification reaction occurring.

[0025] The control system may be configured to balance the gasification reaction of the biomass particles with the available concentrated solar energy and additional variable parameters of a fixed range of particle size, temperature of the chemical reactor, and residence time of the particles in a reaction zone in the chemical reactor. 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.

[0026] One or more detectors indicate an amount of solar energy available in different areas of the chemical reactor to guide the control system in balancing an amount of the biomass particles flowing in each of the reactor tubes.

[0027] In various embodiments, the control system can use both feedforward (based on anticipated changes) and feedback (based on actual measured changes) elements to control the balancing of the gasification reaction occurring to result in negligible tar formation in resultant syngas products and waste products. Control strategies discussed herein have been developed to manage a variation in solar energy due to changes in solar energy and a cyclic operating state. Some embodiments include two or more sensors including temperature sensors at the entrance and exit of the chemical reactor and one or more light meters to provide information to the feedback portion of the computer control. This information indicates a feedback portion of the amount of solar energy available indicated to the control system. The feed forward system indicates an expected amount of solar energy available indicated to the control system in the long and short term.

[0028] The control system can use the complex feedforward/feedback model-predictive scheme to ensure that temperature of the reactor cavity remains in the required range. The feedforward components use meteorological measurements, geographical factors, and time of day/day of year to predict the rate of change of available solar energy and make process adjustments accordingly. Additionally, the feedback component of the control system checks these predictions against real time data to make appropriate corrections balanced by not overcorrecting or under correcting for the instantaneous changes in solar energy conditions.

This control approach gives robust system operation with a highly transient system input: Sunlight.

[0029] In some embodiments, a feed demand signal from the control system can be used to control the feed rate of particles of biomass in the solar driven chemical reactor. This control can be performed using a feedforward/feedback model-predictive scheme. The scheme is aided by knowing an amount surface area, thermal mass, and heat capacity in the multiple tubes and receiver cavity to ensure that temperature of the reactor cavity remains in the operational temperature range of below 1600 degrees C and above 800 degrees C. These temperatures might be maintained during rapidly changing daily weather conditions. In some examples, the feed forward model can predict a maximum, minimum, and average available solar energy over each time period in a given day as well as each day throughout the year.

[0030] A feedforward portion and a feedback portion of the control system may be used to adapt for both long and short term disturbances in available solar energy. For example, the feedforward portion may anticipate cyclic changes in solar energy due to at least a time of day, day of the calendar it is, and periodic weather reports, such as daily or hourly weather reports. The anticipation may be generated with a predictive model that adapts to the anticipated cyclic changes. Additionally, the system may compensate for missing data, such as missing weather reports.

[0031] The feed-forward portion utilizes a histogram of events affecting an amount of available solar energy categorized into at least three general time durations. Events may further be categorized as short events of 1 to 5 hours, often caused by passing clouds; medium events of 5-14 hours, often caused by diurnal effects (for our mid latitudes), long term events of 14 hours or more, generally caused by more major weather events. The time of day, the day of the calendar and the daily weather report may also be considered with respect to feed-forward implementations. Additionally, in some embodiments, diurnal effects may be considered by the feed-forward implementation. Diurnal effects can relate to or occur within a 24-hour period each day and including the predictable sunrise and sunset for daytime hours in a daily period.

[0032] The feedback portion measures actual process parameters including 1) various temperature parameters about the reactor including the operating temperature at an entrance and an exit of the chemical reactor, 2) the amount of concentrated light focused at or received at the windows and/or open apertures, 3) chemical composition of products coming out of the reactor and other similar parameters, and then supplies these measurements to the control system in the balancing of the gasification reaction of biomass particles. The feedback portion of the control system may receive the dynamic feedback from the sensors and combine this data in order to maintain both the quality and output of resultant syngas at above a threshold set point of substantial tar destruction to less than 50 mg/m^3 and complete gasification of greater than 90 percent of the carbon content of the biomass particles into the reaction products. Note, the temperature sensors in the receiver may equally correlate temperature of various locations within the reactor. Both temperature sensors in the receiver and the reactor may be used as an indication of actual reaction temperature.

[0033] Additional parameters are known by the control system such as enough surface area and thermal mass of the cavity and reactor tubes is built into the multiple tubes and receiver cavity in relation to the feed rate of biomass particles, to act as a ballast, averaging out very short term small fluctuations (second to second) in the available solar energy to have a very low ramp-up and ramp-down of temperature of the reactor due to these instantaneous changes in available solar energy. This can allow the ramp-up and ramp-down of the feed rate of biomass particles to be gradual as well.

[0034] One factor determinant in energy delivered by radiation to the reacting particles, extent of reaction, and extent of tar mitigation is reaction temperature. The receiver cavity temperature may be a controllable parameter. Because the heliostat field has a much longer response time (approximately 1-5 minutes) than does the solar energy source (can vary within 30 seconds), the reaction temperature may be controlled by modulating the biomass flow rate through the reactor tubes. If reaction temperature starts to drop, feed rate is decreased, reducing the reaction sink and allowing the temperature to recover. The opposite is performed for over-temperature. The thermal mass of the cavity and reactor tubes acts as a ballast, averaging out very short term small fluctuations (second to second) in the available solar energy. Flow rate fluctuations in the syngas production rate occur as well. In the case of slight underfeeding, product composition will not change, but overfeeding can lead to a drop in temperature that can allow tars to pass out of the reactor undestroyed.

[0035] A composition analyzer at the exit of the system will sense changes in methane or tar composition. Upon readings of compositions that are too high, the control system can divert the products to a flare to avoid damage to the compressors and catalytic systems in the methanol synthesis plant. The composition analyzer at the exit of the reactor system may be used to sense changes in hydrogen, carbon monoxide, methane and tar composition of the syngas. The composition analyzer provides a dynamic signal to the feedback portion of the control system. Upon readings of methane and tar composition of the syngas that are too high above a threshold, the control system sends a signal to divert the reactant products of the gasification reaction to a recycling line back into the entrance to the chemical reactor to avoid damage to compressors, catalytic systems, and other components in the methanol synthesis portion of the on-site fuel synthesis reactor. The compressor to the syngas buffer tank may be designated to follow flow rate fluctuations in the syngas production rate as well.

[0036] The control system may send a feed demand signal to the feed system to control a feed rate of the particles of biomass in the solar driven chemical reactor by changing a gas pressure and/or volumetric flow rate of the entrainment carrier gas in combination with a metering device controlling a weight of biomass particles from a lock hopper to the feed lines that feed the chemical reactor. The control system may send a feed demand signal to the feed system to control a feed rate to reactor tubes by isolating that tube or set of tubes from receiving biomass. Thus, tubes individually or in sets of tube may be turned on to have more biomass flowing into the solar driven chemical reactor and turned off/isolated to have less biomass particles flowing into the chemical reactor.

[0037] Control of the multiple reactor tubes may be split into two or more groups of tube subsets, where the control system balances the amount of biomass particles flowing into each of the reactor tubes to an amount of solar energy available by 1) controlling a rotational rate of a screw of a lock hopper feeding the biomass where all the tubes in the tube subset have their feed rate simultaneously turned up or turned down, 2) varying an amount of the reactor tube-subsets participating in the gasification reaction by turning on or turning off a flow of particles of biomass from the lock hopper to the reactor tubes making up a tube subset, or 3) a combination of both.

[0038] In an embodiment, a 2-phase pinch valve system may be on each feed line to each reactor tube. The control system balances the amount of biomass particles flowing in each of the reactor tubes to the amount of solar energy available by sending a dynamic feedback control signal to the 2-phase pinch valve system to control an amount of compression of a flexible pipe section of the feed line that the biomass particles are flowing through to control flow in the individual reactor tubes. The detectors indicate the amount of solar energy available to guide the control system.

[0039] 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.

[0040] The solar-driven chemical plant can include a chemical reactor that has multiple reactor tubes 202, 204, 206, 208 in which the biomass particles flow in. Two or more reactor tubes in the chemical reactor tubes might be used. The example illustrated includes five reactor tubes. One or more feed lines supply to the reactor tubes the particles of biomass in the fixed range of particle size controlled to an average smallest dimension size between 50 microns (um) and 2000 um, with a general range of between 200 micrometer and 1000 micrometer. Additionally, the control system maintains the temperature at an exit from the tubes 202, 204, 206, 208 of the chemical reactor at a steady state temperature exceeding 1000 degrees C, above transitory minimum temperature of 800 degrees C and below peak temperatures of 1600 degrees C. Further, the control system monitors the residence time of the particles of biomass in the reaction zone in the chemical reactor, which is between a range of 0.01 and 5 seconds.

[0041] A separate feed line can be used to feed biomass particles for each of the reactor tubes 202, 204, 206, 208 in the chemical reactor 200, which can allow independent temperature control and balancing of the amount of particles of biomass flowing in each of the reactor tubes in the multiple tube solar driven chemical reactor.

[0042] The receiver cavity, the multiple reactor tubes, and the one or more open apertures or windows are shaped and sized to facilitate greater than 75% average aperture/window incident power to be converted into chemical/sensible energy at peak incident power. Thus, greater than 75% the amount of energy entering the receiver 200 as solar energy ends up as chemical or sensible enthalpy leaving the reactor tubes. Also, a conversion of carbon in the particles of biomass to CO (and in some cases, CH4) above 85% yield/ton of the biomass occurs from the gasification reaction.

[0043] The size and shape of one or more apertures in the receiver and a range of operating temperatures of the cavity of the receiver enclosing the chemical reactor can be set to make radiation losses directly calculable. An insulation layer around the cavity may be set thick enough to control conduction losses to, e.g., less than 2% of the peak solar input. Once the chemical reactor is heated up to operational temperatures, due to the conduction losses to less than 2% and the radiation losses being directly calculable, then the receiver cavity temperature is a controlled parameter. The control system then primarily controls by modulating a flow rate of biomass particles through the reactor tubes balanced against the predicted feed-forward available amount of solar energy and the dynamically determined feedback amount of available solar energy.

[0044] The control system may supply a control signal to the feed system, the solar energy concentrating fields, the on-site fuel synthesis reactor and other plant systems. For example the control system signal may direct and receive feedback from 1) the solar concentrating field to alter alignment and an amount of concentrated solar energy supplied, 2) the feed system to alter an amount and or concentration of biomass flowing in the reactor tubes, and/or which sets of reactor tubes are allowing flow of chemical reactants, and thus, participating in the solar driven chemical reaction, 3) various sensors or models for weather events indicating an amount of solar energy available etc. and 4) other similar plant processes discussed herein. All of these factors may be taken into account by a control algorithm in the control system in sending out the control signals to the feed system, the solar energy concentrating fields, etc.

[0045] In some embodiments, the receiver cavity, the multiple reactor tubes, and the one or more apertures or windows are shaped and sized to map an amount of solar flux distribution to the reactor tube size and geometric position to allow essentially a same rate of biomass gasification for a set biomass particle size range everywhere in the reactor, and thus, avoiding locally extremely high temperatures (>1500 ºC) or extremely low temperatures (<600 C).

[0046] A chemical reaction is conducted in a solar driven chemical reactor having multiple reactor tubes using concentrated solar energy to drive the conversion of the chemical reactant. The endothermic chemical reaction conducted in the reactor tubes includes one or more of the following: biomass gasification, steam methane reforming, methane cracking, steam ethane or naphtha cracking to produce ethylene and related olefins, or carbon dioxide reduction or water splitting, using solar thermal energy coming from a concentrated solar energy field. An entrained-flow of chemical reactants into the chemical reactor for the above reactions starts when 1) the solar energy concentrating field is aligned at the aperture of the solar thermal receiver containing the solar driven chemical reactor, and 2) the solar driven chemical reactor is at at least a minimum operational temperature of 800 degrees Celsius and preferably greater than 1000 degrees Celsius. During start up of the integrated chemical plant, temperature of the chemical reactor is raised to get up to an operational temperature of at least 800 degrees C so that the effluent reactant products from the chemical reactor possesses a proper gas composition and quality for downstream chemical processing such as methanol synthesis.

[0047] The control system may utilize different models and/or controls schemes that may be automatically or manually selected depending on the system and variable state. For example, insolation perturbation may be categorized into 3 types: 1) short events, e.g. 0-5 hours, often caused by passing clouds, 2) medium events, e.g. 5-14 hours, often caused by diurnal effects, and 3) long-term events (e.g. 14 hours or more) generally caused by major weather systems and other variables such as, but not limited to, time of day, day of the year, daily weather reports, solar field condition, and biomass type and condition, may be considered by the control system when selecting between and executing different models and/or control schemes. The models and/or control schemes may be fixed, adaptive, replaced, or augmented from time to time.

[0048] Figure 3 illustrates a diagram of an example solar tower 300 with receivers 302 and solar energy concentrating field 304. A solar tower 300 may be used in the solar-driven chemical plant with the entrained-flow biomass feed system. The feed system can be feedstock flexible via, for example, particle size control of the biomass.

[0049] 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 one or more solar energy concentrating fields 304 including 1) an array of heliostats, 2) solar concentrating dishes, and 3) any combination of the two. 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 chemical plant 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.

[0050] The tower 300 supports the elevated solar thermal receiver 302 and solar driven chemical reactor 306. The tower 300 is tall enough, such as at least 150 meters, in height to give an optimized angle of elevation for the solar energy concentrating fields 304.

[0051] The solar-driven chemical reactor system can include a non-uniform heliostat field has >25,000 m^2 of reflecting surface, >50,000 m^2 of reflecting surface, or >100,000 m^2 of reflecting surface, that cooperates with the solar thermal receiver to have an ability to control an amount of solar energy flux across the apertures or windows. Reflectors with other total reflective surfaces areas may also be used.

[0052] The reflecting surface cooperates with the solar thermal receiver to have an ability to control an amount of solar energy flux across the apertures or windows that is applied to reactor tubes and cavity walls to allow enough energy from a radiant energy to raise the heat. This increase in the heat may initiate and sustain a sufficiently high temperature so that complete gasification occurs of greater than 90 percent of the carbon content of the biomass particles into reactant products. The reactant products can include hydrogen and carbon monoxide gas in the very short residence time between the range of 0.01 and 5 seconds. The size and a shape of the one or more apertures or windows can determined by the heliostat field trying to focus into the apertures or windows a total amount of light in sun concentrations that is needed for the short residence times balanced against an efficiency of a solar energy being concentrated from the non-uniform heliostat field. The control system configured to balance the chemical reaction with the available concentrated solar energy.

[0053] In some embodiments, each heliostat has a mirror and the array of mirrors in the heliostat field are configured to obtain both 1) dense packing in at least the first third of the part of the field near the receiver and 2) optimal small shading. The first third of the part of the field has the highest proportion of energy off of each of the mirrors. The concentrated solar energy from this dense packed portion of heliostats intercepts the one or more apertures or windows of the receiver. The remainder of the field is aimed at the one or more apertures or windows of the receiver but proportionately provide less solar energy.

[0054] Optimal small shading and minimal blocking also occurs for the mirrors in the heliostat field due to 1) the angle of elevation of the heliostat field to the solar thermal receiver on the tower, in combination with 2) the staggered heights and 3) the spacing of the rows of the non-uniform heliostat field. The heliostat field can receive control signals from the control system to control an alignment of the field relative to the solar receiver. The heliostat field may supply signals such as an amount of available solar energy to the control system.

[0055] Some embodiments can include one or more actuators on the heliostats and/or on the receiver. The one or more apertures can be articulated moveable apertures that are capable of varying location on the solar thermal receiver, e.g., on top of the tower 300.

These movements may depend on the time of day or season of the year and be based on the actuators moving the apertures.

[0056] A model of solar energy flux can be used to map the apertures with respect to the solar power delivered to the aperture changes over time under similar natural solar conditions in order to assist the control system in guiding the actuators in moving the apertures and/or heliostats.

[0057] One or more structures with high temperature storage material that absorb the concentrated solar energy contained within the receiver chamber may be used. The structures may be used as radiant heat masses to keep the chemical reactor 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 more stable/less transient during normal operation. One or more of these radiant heat masses can be positioned in the cavity in areas of extremely high concentrated solar energy compared to other areas within the cavity to absorb some of the concentrated solar energy in that area to allow the reactor tubes to all use the same material.

[0058] In some embodiments, a material making up the reactor tubes can possess high emissivity such as 0.7 emissivity coefficient or better, high thermal conductivity such as 30 watts per meter-Kelvin or better, at least moderate heat capacity of 8 joules per mole–degree Kelvin or better. The material can also be resistant to the oxidizing air environment in the cavity and the reducing environment of the biomass gasification reaction inside the tubes in order to support operating temperatures within the tubes in the tar-cracking regime between 1000-1300 ºC. This operating temperature eliminates any need for tar cracking equipment downstream of the chemical reactor. In addition, operation at the high operating temperature in the reactor tubes improves heat transfer, eliminates methane from the exit gases, and decreases required residence time of the biomass particles to achieve complete gasification, which in turn decreases a physical size of the chemical reactor.

[0059] One or more apertures 1) open to the atmosphere or 2) covered by windows can be part of a receiver outer shell that at least partially encloses the multiple reactor tubes 202, 204, 206, 208. Additionally, a material making up the receiver inner wall absorbs, including a black body, or the material highly reflects, including refractory alumina plate, the concentrated solar energy. This causes the radiant heat and then generally radiatively conveys that heat like an oven to the biomass particles in the reactor tubes. The inner wall may operate at high (>1200 °C) wall temperatures and the insulation thickness is designed so as to limit losses through conductive heat loss to less than 2% of the energy incident at peak solar input on the receiver apertures or windows.

[0060] The solar thermal receiver may further include a thick layer of insulation that limits heat losses by conduction from a cavity of the receiver and a moveable insulative door on the receiver aperture limits heat losses by radiation from the cavity during periods of inclement weather or during nighttime, so that the temperature in the cavity is decreased by less than 400 °C in a 12 hour period when no concentrated solar energy is directed at the cavity aperture. Maintaining an elevated temperature in the receiver reduces the amount of time required to heat the receiver following a down period and the thermal shock and stresses imparted to the receiver and reactor materials of construction. In some embodiments, the receiver may include a pump to pump molten salts through tubes in the receiver walls for use in electrical power generation.

[0061] In some embodiments, an aperture design, orientation, and cavity working fluid (buoyancy) may be set to control convective losses The cavity may at least partially enclosing the multiple reactor tubes and may acts like an oven, spreading heat flux around through radiation. The oven effect of the cavity, along with the particles, may tend to average energy amongst themselves at their design volumetric loadings and combine to give a fairly uniform temperature profile and subsequent fairly uniform reaction profile of the biomass particles.

[0062] The control system is configured to take all of the above into consideration when balancing the chemical reaction needs with the available concentrated solar energy.

[0063] 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. The average size of ground particles may be correlated to filter particle size used in standard filter ranges.

[0064] As the gasification is performed through indirect heating, the cavity and tube walls must be able to efficiently conduct solar energy through themselves and radiate 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.

[0065] In some embodiments, 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. These processes include at least the following three stages: A) pyrolysis of the carbonaceous biomass particles into 1) carbonaceous char and

2) volatile components vaporized into gas products; B) complete gasification of the carbonaceous char including lignin fractions into 1) gaseous products including carbon monoxide, hydrogen, and tars as well as 2) greater than 99 % pure carbonaceous ash; and C) cracking of the tars including larger hydrocarbons and aromatic compounds collectively known as tars. This gasification can occur at greater than 1000 degrees C to the produce the substantial tar destruction to less than 50 mg/m^3 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. The steps of complete gasification and cracking of tars starts and finishes within the residence time of the biomass particles in the reaction zone in the chemical reactor between the range of 0.01 and 5 seconds.

[0066] As discussed above, in various embodiments complete gasification of the carbonaceous char including lignin occurs. Lignin is a complex chemical compound derived from biomass, and an integral part of the secondary cell walls of plants. Lignin fills the spaces in the cell wall between cellulose, hemicellulose, and pectin components. Additionally, preheating of the biomass prior to being fed into the reactor tubes may raise the temperature above 200 degrees C beginning the pyrolysis process. Thus, at least the last two steps may start and finish within the residence time within the reactor tubes.

[0067] In an embodiment, 1) a material and 2) an indirect gasification design of the heat radiation from the multiple reactor tubes and walls of the receiver allows for feedstock flexibility in the type of biomass making up the particles of biomass. This can obviate a need for an exothermic/endothermic reaction balancing because the heat radiation from the concentrated solar energy absorbed or highly reflected by the walls and tubes primarily drives the endothermic gasification reaction and the heat radiation-based heat transfer balancing makes the endothermic reaction gasification quite forgiving in terms of internal reaction balance. Thus, at least two or more different types of biomass materials might be used in the same reactor tube geometry. This may obviate any need for a complete reengineering when a new type of biomass feedstock is used. The two or more different types of biomass materials that can be fed from the feed system, individually or in combinational mixtures, are selected 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, source separated green wastes and other similar biomass sources. These sources might be used interchangeable as long as a few parameters are controlled such as the particle size of the biomass and temperature of the chemical reactor. The complete gasification of the particles of miscanthus may be equal to or greater than 94% when miscanthus is fed and the complete gasification of the particles of rice straw is equal to or greater than 98% when rice straw is fed from the feed system.

[0068] Different chemical reactants may be fed with the biomass, such as methane, natural gas, steam, etc. The control system may be configured to balance chemical reaction types, such as a biomass gasification reaction, a stream reforming reaction, a dry reforming reaction and various combinations of these reactions within the solar driven chemical reactor, to an amount of concentrated solar energy available directed at the solar thermal receiver in order to keep the solar chemical reactor at a temperature at which the chemical reactor operates high enough to maintain the generated syngas within the desired molar ratio of H2 to CO ratio with being substantially tar free and having less than 7% by volume CO in the generated syngas.

[0069] The control system for the solar driven chemical reactor and its multiple reactor tubes factors in many parameters in its control algorithms for chemical reactor operation. The control system controls balancing of mass in and energy needed to drive various chemical reactions verses available concentrated solar energy because each endothermic reaction consumes an amount of available energy AND the algorithm controls concentration/amount of each reactant product into the chemical reactor to control the molarity and ratio of the reactants going into the reactions in order to control the products coming out of the reactions, AND the algorithm may control what chemical reactants are being supplied to the reactor and thus what chemical reactions are occurring within multiple reactor tubes.

[0070] The endothermic chemical reaction conducted in to the solar driven chemical reactor includes one of the following: biomass gasification, steam methane reforming, methane cracking, steam ethane cracking to produce ethylene, metals refining, carbon dioxide capture and other similar endothermic carbon-based chemical reactions can be conducted in this reactor using solar thermal energy.

[0071] Note, the control system and reactor tubes may be configured to the produce hydrogen and carbon monoxide products from one or more of the following reactants in the tubes 1) biomass particles and steam, 1) biomass particles, methane and steam (SMR), or methane and carbon black particles.

[0072] In some embodiments, a carrier gas supply line can supply the entrainment gas as a pressurized dry steam. Natural gas may be fed along with the biomass particles during a co-gasification of 1) biomass in the presence of steam and 2) steam reforming of natural gas, and the pressurized dry steam is generated from waste heat recovered from either 1) 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.

[0073] In some embodiments, a stoichiometric ratio of steam may be injected along with the particles of biomass into the reactor tubes during the gasification reaction to shift some of the product carbon monoxide to additional hydrogen and carbon dioxide gas, making the hydrogen to carbon monoxide ratio appropriate for methanol synthesis by the onsite fuel synthesis reactor. In such an embodiment, the inside walls of the reactor tubes may be are made of corrosion resistant materials with a resistance to steam of between a good to excellent rating.

[0074] Figure 5 illustrates a diagram of a solar thermal receiver 500 with gasifier tubes 502. The solar-driven chemical plant can include a solar driven chemical reactor 502, a solar thermal receiver 500, or both. In some embodiments, solar thermal receiver 500 can enclose the multiple reaction tube downdraft chemical reactor. Additionally, the feed system may feed biomass particles into the multiple reaction tubes 502, in which the particles of biomass may be gasified in the presence of steam at a temperature exceeding 950 degrees C from an exit of a gasification reaction zone of the reactor tubes.

[0075] Some embodiments may include one or more apertures 1) open to an atmosphere of the Earth or purge gas environment in the cavity or 2) covered by more windows. The apertures and windows act 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 transfer energy by solar radiation absorption and heat radiation, convection, and conduction to the reacting particles.

[0076] The length and diameter dimensions of a gasification reaction zone of each of the reactor tubes, along with an arrangement and an amount of the tubes are matched to an amount of sun concentration from the heliostat field to give the fast residence time of 0.01 second to 5 seconds, with the preferred residence time of 2-3 seconds at the biomass gasification temperatures.

[0077] 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 a biomass into reactor, for example, drop tube, total solid feed into the reactor, slurry fed into the reactor, a moveable bed in the reactor, or combinations of these schemes.

[0078] One or more feeding vessels in the biomass feed system supply two or more reactor tubes in the solar-driven chemical reactor. Each of the feeding vessels has one or more outlets configured to supply a consistent volumetric amount of biomass particles.

[0079] One example solar-driven chemical plant may include the entrained-flow biomass feed system 600 that includes or otherwise cooperates with a grinding system. The grinding process 603 and feed process may be 1) processes separated in time and completed independently of the other process or 2) a continuous process of the where the grinding process 603 occurs and immediately feeds biomass into the feed system and then into the chemical reactor.

[0080] An objective of the feeding system is to feed as many reactor tubes as possible with the fewest number of feeding vessels such as lock-hopper systems.

[0081] The grinding system 603 has a mechanical cutting device used to grind the biomass into primary particles, which are to be fed into the solar driven chemical reactor. The grinding system supplies primary particles that have an average smallest dimension size between 200 microns (um) and 2000 um, with a general range of between 500 um and 1000 um to a lock hopper system 604 with a standard belt conveyer. The biomass particles are then fed across a pressure boundary into a pressurized entrainment gas for feeding into in the solar driven chemical reactor. The feeding vessel may use an Auger/Screw feeder or an airlock-type rotational solids feeding/rate metering device.

[0082] As illustrated in Figure 6a, the entrainment-flow biomass feed system 600 can include a pressurized lock hopper 604 that feeds the biomass to a rotating screw conveyor 602 and a metering device and then into an entrainment gas pipe at the lock hopper exit

606. A flow splitter distributes the particles of biomass into multiple entrainment gas lines to feed at least two or more of the multiple reactor tubes making up the solar driven chemical reactor. The entrainment gas for the pneumatic biomass feed system may be a pressurized dry steam generated from waste heat recovered from either 1) the methanol/Methanol-To-Gasoline (MTG) units in the hydrocarbon fuel synthesis process or 2) the products from the gasification reaction in the solar driven chemical reactor. The entrainment gas may also be CO2, natural gas, an inert gas, steam generated in any fashion, or other similar entrainment gas.

[0083] Additionally, an entrained-flow biomass feed system having one or more feed lines to feed the biomass particles into the multiple reactor tubes, in which a separate entrainment line and metering device of the entrained-flow biomass feed system is used for each of the gasifier reactor tubes in the chemical reactor. This may allow for balancing of 1) amount of particles of biomass flowing through the feed line to each reactor tube to 2) an amount of solar energy available for that reactor tube in the multiple tube solar driven chemical reactor. Feed rate of the biomass particles can be controlled by a metering device and controlling a rotational rate of a screw 602 at a base of the lock hopper 604, which responds to a feed demand signal received from the control system.

[0084] Thus, control of the rotational rate of the screw or auger 602 can move set amounts of biomass along the axis of rotation of the auger 602. The auger 602 may be located at the base of the lock hopper 604 and can be controlled by a control system to respond to feed demand of the system. As discussed, the control system controls the feed rate of particles of biomass in the solar driven chemical reactor based on an amount of solar energy available indicated by sensors including temperature sensors and/or light meters.

[0085] In some embodiments, the shape and width of the outlet of the feed line pipe carrying the biomass particles to its corresponding reactor tube may be used to control a dispersion pattern of biomass particles entering each reactor tube. Greater than 90 % conversion may occur because of both 1) the high operating temperatures and 2) that the biomass particles are well separated from one another in a flowing dense cloud of very fine biomass particles. An amount of oxygen, air, or steam co-currently flowing in the gasification of the biomass particles can be controlled to cause a selectivity of carbon reactant from the biomass to become CO rather than CO2 at better than a 10:1 selectivity to CO over CO2.

[0086] Figure 7 illustrates a diagram of a solar-driven chemical plant 800. In such a system solar power from a concentrating field 802 may be provided through a window or aperture 804 to a solar heated reactor chamber 806. A quencher 808 may be used to prevent back reaction. 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.

[0087] In reactor 806 biomass particles can be reduced to syngas, which in turn can be synthesized into liquid fuel in liquid fuel synthesizer 808. Additionally, an example system may store concentrated solar energy in chemical bonds by using the solar energy to produce a liquid hydrocarbon fuel. Liquid hydrocarbon fuel is generally easily storable and transportable. Examples of liquid hydrocarbon fuel include, but are not limited to one or more of jet fuel, DME, gasoline, diesel, methanol, and mixed alcohol, synthetic natural gas production, and heating oil generation.

[0088] Figure 8 illustrates a flow diagram. 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 the bales (loaded by conveyer) into primary particles.

The re-ground particles have an average size between 500 um and 1000 um, and are loaded into the lock hopper system with a standard belt conveyer.

[0089] 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. 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.

[0090] 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.

[0091] 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.

[0092] Some embodiments of the solar-driven chemical plant include a spray nozzle to supply water to the product gas exiting the chemical reactor to shift some of the product carbon monoxide to additional hydrogen and carbon dioxide gas in a water gas shift reaction, making the hydrogen to carbon monoxide ratio appropriate for methanol synthesis, such as a H2:CO ratio in the synthesis gas within the range 2.0 to 2.7.

[0093] An insulation layer around the receiver can include resistance heaters connected to the outer wall of the receiver to assist with maintaining temperature in the 800-1600 degree C range. Waste heat from a quenching unit quenching the gasification products heats high temperature storage material in hot beds in an exit of the receiver, which is used with molten salts for use in electrical power generation. The electrical power may be a source of power for the resistance heaters. The control system can turn on and off the resistance heaters as additional heat sources for maintaining temperature as need be. The control system supplies a control signal to 1) the feed system, 2) the solar energy concentrating fields, 3) and the supplemental resistance heating system 4) potentially to a recirculation system, and 5) other systems. The lag times and response times of the: 1) solar energy concentrating fields to alter alignment and an amount of concentrated solar energy supplied, 2) feed system to alter an amount of biomass flowing in the reactor tubes, 3) time for weather events to alter an amount of solar energy available, such as 30 seconds for a cloud, are factors taken into account by a control algorithm in the control system in sending out the control signals to the feed system, the solar energy concentrating fields and the supplemental resistance heating system.

[0094] 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.

[0095] The control system may operate in a networked environment using logical connections to one or more remote computers, such as a remote computer. The remote computer may be a personal computer, a hand-held device, a server, a router, a network PC, a peer device or other common network node, and typically includes many or all of the elements described above relative to the computer.

[0096] 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.

[0097] Some portions of the detailed descriptions above are presented in terms of algorithms and symbolic representations of operations on data bits within a computer memory. These algorithmic descriptions and representations are the means used by those skilled in the data processing arts to most effectively convey the substance of their work to others skilled in the art. An algorithm is here, and generally, conceived to be a self-consistent sequence of steps leading to a desired result. The steps are those requiring physical manipulations of physical quantities. Usually, though not necessarily, these quantities take the form of electrical or magnetic signals capable of being stored, transferred, combined, compared, and otherwise manipulated. It has proven convenient at times, principally for reasons of common usage, to refer to these signals as bits, values, elements, symbols, characters, terms, numbers, or the like. These routines, algorithms, etc. may be written in a number of different programming languages. Also, an algorithm may be implemented with lines of code in software, configured logic gates in software, or a combination of both. The portable application and its security mechanisms may be scripted in any number of software program languages. Unless specifically stated otherwise as apparent from the above discussions, it is appreciated that throughout the description, discussions utilizing terms such as "processing" or "computing" or "calculating" or "determining" or "displaying" or the like, refer to the action and processes of a computer system, or similar electronic computing device, that manipulates and transforms data represented as physical (electronic) quantities within the computer system's registers and memories into other data similarly represented as physical quantities within the computer system memories or registers, or other such information storage, transmission or display devices.

[0098] 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 that manages variations in solar energy, comprising:

a solar thermal receiver aligned to absorb concentrated solar energy from one or more solar energy sources including 1) a single mirror, heliostat, or solar-concentrating dish, 2) an array of heliostats, 3) two or more solar-concentrating dishes, and 3) any combination of the three;

a solar driven chemical reactor at least partially contained within the solar thermal receiver;

an entrained gas biomass feed system that uses an entrainment carrier gas and supplies a variety of biomass types fed as particles into the solar driven chemical reactor;

inner walls of the solar thermal receiver and the chemical reactor made from materials selected to transfer energy by primarily heat radiation, along with convection, and conduction to the reacting biomass particles to drive the endothermic gasification reaction of the particles of biomass flowing through the chemical reactor;

a control system configured to balance the gasification reaction of biomass particles with the available concentrated solar energy and additional variable parameters including a fixed range of particle sizes, operating temperature of the chemical reactor, and residence time of the particles in a reaction zone in the chemical reactor so that an overall biomass particle conversion remains above a threshold set point of greater than 90 percent of the carbon content of the particles into reaction products that include hydrogen and carbon monoxide gas; and

a feedforward portion and a feedback portion of the control system configured to adapt for both long and short term disturbances in available solar energy, wherein the feedforward portion anticipates cyclic changes in solar energy due to at least a time of day, day of the year, short-term cloud, dust, smoke or other obscuring events, or long-term weather events, with a predictive model that adapts to the anticipated cyclic changes, and wherein the feedback portion measures actual process parameters including the operating temperature of the chemical reactor and then uses these measurements in the balancing of the gasification reaction of biomass particles.

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

one or more temperature sensors to detect the operating temperature of the chemical reactor at an entrance and an exit and supply that measurement to the feedback portion of the control system,

two or more reactor tubes in the chemical reactor in which the biomass particles flow in and located within the solar thermal receiver,

one or more feed lines which supply to the reactor tubes the particles of biomass in the fixed range of 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,

wherein the control system maintains the temperature of the tubes of the chemical reactor at a steady state temperature exceeding 1000 degrees C, above transitory minimum temperature of 800 degrees C and below peak temperatures of 1600 degrees C,

wherein the control system balances the gasification reaction of biomass particles with the available concentrated solar energy so that the overall biomass particle conversion temperature remains above a threshold set point of substantial tar destruction resulting in less than or equal to 50 mg/Nm^3 of tar and the gasification of greater than 90 percent of the carbon content of the particles, and where the residence time of the particles of biomass in the reaction zone in the chemical reactor is between a range of 0.01 and 5 seconds.

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

an amount of solar energy available indicated by one or more temperature sensors in the chemical reactor and one or more light meters to provide the actual process parameters information to the feedback portion of the control system;

two or more reactor tubes in which gasification occurs in a vertical orientation in the chemical reactor in which the gasification occurs;

a separate feed line is used to feed biomass particles for each of the reactor tubes in the chemical reactor, which allows independent temperature control and balancing of amount of particles of biomass flowing in each of the reactor tubes in the multiple tube solar-driven chemical reactor;

a lock hopper system in the feed system, where the particles of biomass feed are distributed to the separate carrier gas entrainment line by the lock hopper feed system, in which feed rate of the biomass particles is controlled by a metering device, which responds to a feed demand signal received from the control system; and

an on-site chemical 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 fuel synthesis process to create one or more of 1) a liquid hydrocarbon or alcohol fuel, 2) solid fuel, 3) liquid chemicals, 4) solid chemicals.

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

a lock hopper having a metering device in a feed system having one or more feed lines coupled to the chemical reactor, wherein the control system sends a feed demand signal to the feed system to control a feed rate of the particles of biomass in the solar driven chemical reactor, where control of the multiple reactor tubes is split into two or more groups of tube subsets, where the control system balances the amount of biomass particles flowing into each of the reactor tubes to an amount of solar energy available by 1) controlling a rotational rate of a screw of a lock hopper feeding the biomass where all the tubes in the tube subset have their feed rate simultaneously turned up or turned down, 2) varying an amount of the reactor tube-subsets participating in the gasification reaction by turning on or turning off a flow of particles of biomass from the lock hopper to the reactor tubes making up a tube subset, or 3) a combination of both.

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

a spray nozzle to supply water to the product gas exiting the chemical reactor to shift some of the product carbon monoxide to additional hydrogen and carbon dioxide gas in a water gas shift reaction, making the hydrogen to carbon monoxide ratio appropriate for the planned syngas use.

6. The solar-driven chemical plant of claim 2, wherein the control system is configured to balance chemical reaction types, including the biomass gasification reaction, a stream reforming reaction, a dry reforming reaction and various combinations of these reactions within the solar driven chemical reactor, to an amount of concentrated solar energy available directed at the solar thermal receiver in order to keep the solar chemical reactor at a temperature at which the chemical reactor operates high enough to maintain the generated

syngas within a set molar ratio of H2 to CO ratio of 2.1 to 2.8, with being substantially tar free having less than 200 Mg/M^3, and having less than 7% by volume CO in the generated syngas.

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

an amount of surface area, thermal mass, and heat capacity is built into the receiver and can be in the form of the receiver walls, insulation, or reactor tubes;

one or more temperature sensors at the entrance and/or exit of the reactor tubes;

an operational temperature range of below 1600 degrees C and above 800 degrees C in the chemical reactor during daily weather conditions, which are subject to rapid changes in solar availability; and

a feed demand signal from the control system to control the feed rate of particles of biomass in the solar driven chemical reactor by the feedforward/feedback model-predictive scheme in cooperation with designing in enough surface area, thermal mass, and heat capacity in the multiple tubes and receiver cavity to ensure that temperature of the reactor cavity remains in the operational temperature range of below 1600 degrees C and above 800 degrees C during the rapidly changing daily weather conditions, wherein the feed forward model predicts an available solar energy over each time period in a given day as well as each day throughout the year, the feedback portion receives dynamic feedback from sensors, including temperature sensors, and they are combined to maintain both the quality and output of resultant syngas at above the threshold set point of substantial tar destruction resulting in less than or equal to 50 mg/m^3 and complete gasification of greater than 90 percent of the carbon content of the biomass particles into the reaction products, wherein the enough surface area and thermal mass of the cavity and reactor tubes is built into the multiple tubes and receiver cavity, to act as a ballast, averaging out very short term small fluctuations (second to second) in the available solar energy to have a negligible ramp-up and ramp-down of temperature of the receiver and reactor due to these instantaneous changes in available solar energy, thereby allowing the ramp-up and ramp-down of the feed rate of biomass particles to be more gradual as well.

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

an insulation layer around the cavity is set thick enough to control conduction losses to less than 5% of the peak solar input, wherein the receiver cavity temperature is a controlled parameter, which the control system then primarily controls by modulating a flow rate of biomass particles through the reactor tubes balanced against the predicted feedforward available amount of solar energy and the dynamically determined feedback amount of available solar energy.

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

a composition analyzer at the exit of the reactor system to sense changes in the hydrogen, carbon monoxide, carbon dioxide, methane, tar composition, or any combination thereof of the syngas, where the composition analyzer provides a dynamic signal to the feedback portion of the control system and upon readings of any of the hydrogen, carbon monoxide, carbon dioxide, methane, tar compositions of the syngas that are above a threshold, where the control system sends a signal to divert the reactant products of the gasification reaction to a recycling line back into the entrance to the chemical reactor to avoid damage to filters, compressors, catalytic systems, and other components in the downstream portions of the solar gasification and/or liquid fuel and/or chemical synthesis process.

10. The solar-driven chemical plant of claim 1, wherein the biomass 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:

pyrolysis of the biomass particles into 1) carbonaceous char and 2) volatile components vaporized into gas products;

gasification of the carbonaceous char including lignin fractions into gaseous products including carbon monoxide, hydrogen, and tars; and

cracking of the tars, including larger hydrocarbons and aromatic compounds collectively known as tars, at greater than 1000 degrees C to produce substantial tar destruction resulting in less than or equal to 50 mg/m^3 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, wherein the steps of complete gasification and cracking of tars starts and finishes within the residence time of the biomass particles in the reaction zone in the chemical reactor between the range of 0.01 and 5 seconds.

11. The solar-driven chemical plant of claim 3, further comprising:

one or more detectors indicate an amount of solar energy available in different areas of the solar receiver to guide the control system in balancing an amount of the biomass particles flowing in each of the reactor tubes;

a 2-phase pinch valve system on each feed line to each reactor tube, wherein the control system balances the amount of biomass particles flowing in each of the reactor tubes to the amount of solar energy available by sending a dynamic feedback control signal to the 2-phase pinch valve system to control an amount of compression of a flexible pipe section of the feed line that the biomass particles are flowing through to control flow in the individual reactor tubes, and where the detectors indicate the amount of solar energy available to guide the control system; and

wherein an on-site fuel synthesis process has an input to receive a filtered form of the hydrogen and carbon monoxide gas from the reaction products and process them to store the concentrated solar energy in chemical bonds of the biomass as an easily storable and transportable liquid hydrocarbon fuel, where the liquid hydrocarbon fuel is one or more of jet fuel, DME, gasoline, diesel, methanol, mixed alcohol, synthetic natural gas, heating oil, and synthetic crude oil.

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

a shape and width of the outlet of the feed line pipe carrying the biomass particles to its corresponding reactor tube to control a dispersion pattern of biomass particles entering each reactor tube and the greater than 90% gasification of the carbon content of the particles occurs because of both 1) the high operating temperatures of greater than 1000 degrees C and 2) that the biomass particles are well separated from one another in a flowing disperse cloud of very fine biomass particles; and

wherein the resulting CO to CO2 ratio is controllable through a range of greater than or equal to 5:1.

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

a material making up the reactor tubes possesses high emissivity of 0.8 emissivity coefficient or better, high thermal conductivity of 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 the oxidizing air environment in the solar receiver cavity and the reducing environment of the biomass gasification reaction inside the tubes in order to support operating temperatures within the tubes in the tar cracking regime between 800-1350 degrees C, wherein this operating temperature eliminates any need for tar cracking equipment downstream of the chemical reactor, and where in addition the operation at the high operating temperature in the reactor tubes improves heat transfer, minimizes methane from the exit gases, and decreases required residence time of the biomass particles to achieve complete gasification, which in turn decreases a physical size of the chemical reactor itself.

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

a material or materials and an indirect solar gasifier design of the multiple reactor tubes allows for feedstock flexibility in the type of biomass making up the particles of biomass, and obviates any need for an exothermic/endothermic reaction balancing in the chemical reactor design because the concentrated solar energy drives the endothermic gasification reaction and a radiation-based heat transfer balancing makes the endothermic reaction gasification quite forgiving in terms of internal reaction balance, and thus, at least two or more different types of biomass materials can be used in the same multiple reactor tube geometry of the chemical reactor, obviating any need for a complete reengineering when a new type of biomass feedstock is used, where the two or more different types of biomass materials that can be fed from the feed system, individually or in combinational mixtures, are selected from the group consisting of rice straw, rice hulls, corn stover, switch grass, wheat straw, miscanthus, orchard wastes, sorghum, forestry thinnings, forestry wastes, agricultural wastes, source separated green wastes and other similar biomass sources, as long as a few parameters are controlled including the particle size of the biomass and operating temperature of the chemical reactor.

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

an insulation layer around the receiver with resistance heaters connected to the solar receiver walls to assist with maintaining temperature in the 800-1600 degree C range,

where waste heat from either the spill of concentrated solar energy not entering the aperture of the receiver, the solar gasification process, or some other available heat-producing process, heats a working fluid that directly or indirectly supplies energy to electrical generation machinery or heats high-temperature storage material that can be a solid, liquid, or gas, which will later be used to heat a working fluid, which directly or indirectly supplies energy to electrical generation machinery, to supply a source of power for including at least the resistance heaters,

where the control system can turn on and off the resistance heaters as additional heat sources for maintaining temperature as need be, wherein the control system supplies a control signal to 1) the feed system, 2) the solar energy concentrating fields, 3) and the supplemental resistance heating system, and

wherein the lag times and response times of the: 1) solar energy concentrating fields to alter alignment and an amount of concentrated solar energy supplied, 2) feed system to alter an amount of biomass flowing in the reactor tubes, and 3) time for weather events to alter an amount of solar energy available, are factors taken into account by a control algorithm in the control system in sending out the control signals to the feed system, the solar energy concentrating fields and the supplemental resistance heating system.

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

a carrier gas supply line that supplies the entrainment gas as a pressurized dry steam, and/or where natural gas is fed along with the biomass particles during a co-gasification of 1) biomass in the presence of steam and 2) steam reforming of natural gas, and the pressurized dry steam is generated from waste heat recovered from either the spill of concentrated solar energy not entering an aperture in the receiver, the solar gasification process, or some other available heat-producing process.

17. The solar-driven chemical plant of claim 2, wherein the control system utilize different models that are selected depending on the system and variable state, and include insolation perturbations categorized into 3 types: 1) short events, including weather events in duration from 0-5 hours 2) medium events, including diurnal events in duration from 5-14 hours, and 3) long-term events in duration more than 14 hours.

18. The solar-driven chemical plant of claim 2, wherein the computerized control system is configured to receive a feedback signal from a set of sensors, an amount of solar energy available indicated by one or more temperature sensors in the chemical reactor and one or more light meters provides the actual process parameters information to the feedback portion of the control system, a feed vessel in the feed system responds to a feed demand signal from the computerized control system, and the computerized control system controls a flow rate of particles of biomass in the solar-driven chemical reactor based on an amount of solar energy available indicated by sensors for the chemical reactor.

19. A method of generating syngas products for a solar-driven chemical plant that manages variations in solar energy, comprising:

focusing concentrated solar energy to a solar driven chemical reactor contained within the solar thermal receiver;

supplying biomass particles into one or more tubes in the solar driven chemical reactor;

driving an endothermic gasification reaction of the particles of biomass flowing through the tubes of the chemical reactor by primarily heat radiation from the inner walls of the solar thermal receiver and the tube surfaces of the chemical reactor by the absorbed concentrated solar energy;

balancing the gasification reaction of biomass particles with the available concentrated solar energy and additional variable parameters of 1) a fixed range of particle size, 2) operating temperature of the chemical reactor, and 3) residence time of the particles in a reaction zone in the chemical reactor so that an overall biomass particle conversion remains above a threshold set point of substantial tar destruction resulting in less than or equal to 50 mg/Nm^3 of tar and gasification of greater than 90 percent of the carbon content of the particles into reaction products that include hydrogen and carbon monoxide gas; and

adapting to short-term disturbances in duration, medium-term disturbances in duration, and long-term disturbances in duration in available solar energy, wherein a control system anticipates changes in solar energy due to at least a time of day, day of year, periodic meteorological reports, solar field condition, and biomass type and condition, with a predictive model that adapts to the anticipated cyclic changes, and wherein a feedback component measures actual process parameters including the temperature of the chemical reactor and uses the these measurements in the balancing the gasification reaction of biomass particles.

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

conducting a chemical reaction in a solar driven chemical reactor having multiple reactor tubes using concentrated solar energy to drive the conversion of the chemical reactant, wherein an endothermic chemical reaction conducted in the reactor tubes includes one or more of the following: biomass gasification, steam methane reforming, methane cracking, steam ethane or naphtha cracking to produce ethylene and related olefins, or carbon dioxide reduction or water splitting, using solar thermal energy coming from a concentrated solar energy field; and

starting an entrained-flow of chemical reactants into the chemical reactor for the endothermic chemical reaction when 1) the solar energy concentrating field is aligned at an aperture of the solar thermal receiver containing the solar driven chemical reactor, and 2) the solar driven chemical reactor is at at least a minimum operational temperature of 800 degrees Celsius and preferably greater than 1000 degrees Celsius.

AMENDED CLAIMS

received by the International Bureau on 22 November 2010 (22.11.2010)

1. A chemical plant, comprising:

a chemical reactor at least partially contained within the thermal receiver;

an entrained gas biomass feed system that uses an entrainment carrier gas and supplies a variety of biomass types fed as particles into the chemical reactor;

inner walls of the thermal receiver and the chemical reactor made from materials selected to transfer energy by primarily heat radiation, along with convection, and conduction to the reacting biomass particles to drive the endothermic gasification reaction of the particles of biomass flowing through the chemical reactor;

a control system configured to balance the gasification reaction of biomass particles with the available energy and additional variable parameters including a fixed range of particle sizes, operating temperature of the chemical reactor, and residence time of the particles in a reaction zone in the chemical reactor so that an overall biomass particle conversion remains above a threshold set point of greater than 90 percent of the carbon content of the particles into reaction products that include hydrogen and carbon monoxide gas; and

where within the chemical reactor an endothermic gasification reaction of the particles of biomass flowing through the tubes of the chemical reactor is driven by primarily heat radiation from the inner walls of the thermal receiver and the tube surfaces of the chemical reactor.

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 sources including 1) a single mirror, heliostat, or solar-concentrating dish, 2) an array of heliostats, 3) two or more solar-concentrating dishes, and 4) any combination of the three;

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;

a feedforward portion and a feedback portion of the control system configured to adapt for both long and short term disturbances in available solar energy, wherein the feedforward portion anticipates cyclic changes in solar energy due to at least a time of day, day of the year, short-term cloud, dust, smoke or other obscuring events, or long-term weather events, with a predictive model that adapts to the anticipated cyclic changes, and wherein the feedback portion measures actual process parameters including the operating temperature of the chemical reactor and then uses these measurements in the balancing of the gasification reaction of biomass particles;

AMENDED SHEET (ARTICLE 19)

one or more temperature sensors to detect the operating temperature of the chemical reactor at an entrance and an exit and supply that measurement to the feedback portion of the control system,

two or more reactor tubes in the chemical reactor in which the biomass particles flow in and located within the solar thermal receiver,

one or more feed lines which supply to the reactor tubes the particles of biomass in the fixed range of 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,

wherein the control system maintains the temperature of the tubes of the chemical reactor at a steady state temperature exceeding 1000 degrees C, above transitory minimum temperature of 800 degrees C and below peak temperatures of 1600 degrees C,

wherein the control system balances the gasification reaction of biomass particles with the available concentrated solar energy so that the overall biomass particle conversion temperature remains above a threshold set point of substantial tar destruction resulting in less than or equal to 50 mg/Nm^3 of tar and the gasification of greater than 90 percent of the carbon content of the particles, and

where the residence time of the particles of biomass in the reaction zone in the chemical reactor is between a range of 0.01 and 5 seconds.

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

two or more reactor tubes in which gasification occurs in a vertical orientation in the chemical reactor in which the gasification occurs;

a separate feed line is used to feed biomass particles for each of the reactor tubes in the chemical reactor, which allows independent temperature control and balancing of amount of particles of biomass flowing in each of the reactor tubes in the multiple tube solar-driven chemical reactor;

a lock hopper system in the feed system, where the particles of biomass feed are distributed to the separate carrier gas entrainment line by the lock hopper feed system, in which feed rate of the biomass particles is controlled by a metering device, which responds to a feed demand signal received from the control system; and

an on-site chemical 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 fuel synthesis process to create one or more of 1) a liquid hydrocarbon or alcohol fuel, 2) solid fuel, 3) liquid chemicals, 4) solid chemicals.

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

a lock hopper having a metering device in a feed system having one or more feed lines coupled to the chemical reactor, wherein the control system sends a feed demand signal to the feed system to control a feed rate of the particles of biomass in the chemical reactor, where control of the multiple reactor tubes is split into two or more groups of tube subsets, where the control system balances the amount of biomass particles flowing into each of the reactor tubes by 1) controlling a rotational rate of a screw of a lock hopper feeding the biomass where all the tubes in the tube subset have their feed rate simultaneously turned up or turned down, 2) varying an amount of the reactor tube-subsets participating in the gasification reaction by turning on or turning off a flow of particles of biomass from the lock hopper to the reactor tubes making up a tube subset, or 3) a combination of both.

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

a spray nozzle to supply water to the product gas exiting the chemical reactor to shift some of the product carbon monoxide to additional hydrogen and carbon dioxide gas in a water gas shift reaction, making the hydrogen to carbon monoxide ratio appropriate for the planned syngas use.

6. The chemical plant of claim 1, wherein the control system is configured to balance chemical reaction types, including the biomass gasification reaction, a stream reforming reaction, a dry reforming reaction and various combinations of these reactions within the chemical reactor, to maintain the generated syngas within a set molar ratio of H2 to CO ratio of 2.1 to 2.8, with being substantially tar free having less than 200 Mg/M^3, and having less than 7% by volume CO in the generated syngas.

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

an amount of surface area, thermal mass, and heat capacity is built into the receiver and can be in the form of the receiver walls, insulation, or reactor tubes;

AMENDED SHEET (ARTICLE 19)

one or more temperature sensors at the entrance and/or exit of the reactor tubes;

an operational temperature range of below 1600 degrees C and above 800 degrees C in the chemical reactor during daily weather conditions, which are subject to rapid changes in solar availability; and

a feed demand signal from the control system to control the feed rate of particles of biomass in the solar driven chemical reactor by the feedforward/feedback model-predictive scheme in cooperation with designing in enough surface area, thermal mass, and heat capacity in the multiple tubes and receiver cavity to ensure that temperature of the reactor cavity remains in the operational temperature range of below 1600 degrees C and above 800 degrees C during the rapidly changing daily weather conditions, wherein the feed forward model predicts an available solar energy over each time period in a given day as well as each day throughout the year; the feedback portion receives dynamic feedback from sensors, including temperature sensors, and they are combined to maintain both the quality and output of resultant syngas at above the threshold set point of substantial tar destruction resulting in less than or equal to 50 mg/m^3 and complete gasification of greater than 90 percent of the carbon content of the biomass particles into the reaction products, wherein the enough surface area and thermal mass of the cavity and reactor tubes is built into the multiple tubes and receiver cavity, to act as a ballast, averaging out very short term small fluctuations (second to second) in the available solar energy to have a negligible ramp-up and ramp-down of temperature of the receiver and reactor due to these instantaneous changes in available solar energy, thereby allowing the ramp-up and ramp-down of the feed rate of biomass particles to be more gradual as well.

AMENDED SHEET (ARTICLE 19)

8. The chemical plant of claim 7, further comprising:

an insulation layer around the cavity is set thick enough to control conduction losses to less than 5% of the peak solar input, wherein the receiver cavity temperature is a controlled parameter, which the control system then primarily controls by modulating a flow rate of biomass particles through the reactor tubes balanced against the predicted feedforward available amount of solar energy and the dynamically determined feedback amount of available solar energy.

9. The chemical plant of claim 7, further comprising:

a composition analyzer at the exit of the reactor system to sense changes in the hydrogen, carbon monoxide, carbon dioxide, methane, tar composition, or any combination thereof of the syngas, where the composition analyzer provides a dynamic signal to the feedback portion of the control system and upon readings of any of the hydrogen, carbon monoxide, carbon dioxide, methane, tar compositions of the syngas that are above a threshold, where the control system sends a signal to divert the reactant products of the gasification reaction to a recycling line back into the entrance to the chemical reactor to avoid damage to filters, compressors, catalytic systems, and other components in the downstream portions of the solar gasification and/or liquid fuel and/or chemical synthesis process.

10. The chemical plant of claim 1, wherein the biomass 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:

pyrolysis of the biomass particles into 1) carbonaceous char and 2) volatile components vaporized into gas products;

gasification of the carbonaceous char including lignin fractions into gaseous products including carbon monoxide, hydrogen, and tars; and

cracking of the tars, including larger hydrocarbons and aromatic compounds collectively known as tars, at greater than 1000 degrees C to produce substantial tar destruction resulting in less than or equal to 50 mg/m^3 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, wherein the steps of complete gasification and cracking of tars starts and finishes within the residence time of the biomass particles in the reaction zone in the chemical reactor between the range of 0.01 and 5 seconds.

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

one or more detectors indicate an amount of solar energy available in different areas of the solar receiver to guide the control system in balancing an amount of the biomass particles flowing in each of the reactor tubes;

a 2-phase pinch valve system on each feed line to each reactor tube, wherein the control system balances the amount of biomass particles flowing in each of the reactor tubes to the amount of solar energy available by sending a dynamic feedback control signal to the 2-phase pinch valve system to control an amount of compression of a flexible pipe section of the feed line that the biomass particles are flowing through to control flow in the individual reactor tubes, and where the detectors indicate the amount of solar energy available to guide the control system; and

wherein an on-site fuel synthesis process has an input to receive a filtered form of the hydrogen and carbon monoxide gas from the reaction products and process them to store the concentrated solar energy in chemical bonds of the biomass as an easily storable and transportable liquid hydrocarbon fuel, where the liquid hydrocarbon fuel is one or more of jet fuel, DME, gasoline, diesel, methanol, mixed alcohol, synthetic natural gas, heating oil, and synthetic crude oil.

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

a shape and width of the outlet of a feed line pipe carrying the biomass particles to its corresponding reactor tube to control a dispersion pattern of biomass particles entering each reactor tube and the greater than 90% gasification of the carbon content of the particles occurs because of both 1) the high operating temperatures of greater than 1000 degrees C and 2) that the biomass particles are well separated from one another in a flowing disperse cloud of very fine biomass particles; and

wherein the resulting CO to CO2 ratio is controllable through a range of greater than or equal to 5:1.

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

a material making up the reactor tubes possesses high emissivity of 0.8 emissivity coefficient or better, high thermal conductivity of 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 the oxidizing air environment in the receiver cavity and the reducing environment of the biomass gasification reaction inside the tubes in order to support operating temperatures within the tubes in the tar cracking regime between 800-1350 degrees C, wherein this operating temperature eliminates any need for tar cracking equipment downstream of the chemical reactor, and where in addition the operation at the high operating temperature in the reactor tubes improves heat transfer, minimizes methane from the exit gases, and decreases required residence time of the biomass particles to achieve complete gasification, which in turn decreases a physical size of the chemical reactor itself.

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

a material or materials and an indirect solar gasifier design of the multiple reactor tubes allows for feedstock flexibility in the type of biomass making up the particles of biomass, and obviates any need for an exothermic/endothermic reaction balancing in the chemical reactor design because the concentrated solar energy drives the endothermic gasification reaction and a radiation-based heat transfer balancing makes the endothermic reaction gasification quite forgiving in terms of internal reaction balance, and thus, at least two or more different types of biomass materials can be used in the same multiple reactor tube geometry of the chemical reactor, obviating any need for a complete reengineering when a new type of biomass feedstock is used, where the two or more different types of biomass materials that can be fed from the feed system, individually or in combinational mixtures, are selected from the group consisting of rice straw, rice hulls, corn stover, switch grass, wheat straw, miscanthus, orchard wastes, sorghum, forestry thinnings, forestry wastes, agricultural wastes, source separated green wastes and other similar biomass sources, as long as a few parameters are controlled including the particle size of the biomass and operating temperature of the chemical reactor.

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

an insulation layer around the receiver with resistance heaters connected to the solar receiver walls to assist with maintaining temperature in the 800-1600 degree C range,

where waste heat from either the spill of concentrated solar energy not entering the aperture of the receiver, the solar gasification process, or some other available heat-producing process, heats a working fluid that directly or indirectly supplies energy to electrical generation machinery or heats high-temperature storage material that can be a solid, liquid, or gas, which will later be used to heat a working fluid, which directly or indirectly supplies energy to electrical generation machinery, to supply a source of power for including at least the resistance heaters,

where the control system can turn on and off the resistance heaters as additional heat sources for maintaining temperature as need be, wherein the control system supplies a control signal to 1) the feed system, 2) the solar energy concentrating fields, 3) and the supplemental resistance heating system, and

AMENDED SHEET (ARTICLE 19)

wherein the lag times and response times of the: 1) solar energy concentrating fields to alter alignment and an amount of concentrated solar energy supplied, 2) feed system to alter an amount of biomass flowing in the reactor tubes, and 3) time for weather events to alter an amount of solar energy available, are factors taken into account by a control algorithm in the control system in sending out the control signals to the feed system, the solar energy concentrating fields and the supplemental resistance heating system.

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

a carrier gas supply line that supplies the entrainment gas as a pressurized dry steam, and/or where natural gas is fed along with the biomass particles during a co-gasification of 1) biomass in the presence of steam and 2) steam reforming of natural gas, and the pressurized dry steam is generated from waste heat.

17. The chemical plant of claim 2, wherein the control system utilize different models that are selected depending on the system and variable state, and include insolation perturbations categorized into 3 types: 1) short events, including weather events in duration from 0-5 hours 2) medium events, including diurnal events in duration from 5-14 hours, and 3) long-term events in duration more than 14 hours.

18. The chemical plant of claim 2, wherein the computerized control system is configured to receive a feedback signal from a set of sensors, an amount of solar energy available indicated by one or more temperature sensors in the chemical reactor

and one or more light meters provides the actual process parameters information to the feedback portion of the control system, a feed vessel in the feed system responds to a feed demand signal from the computerized control system, and the computerized control system controls a flow rate of particles of biomass in the solar-driven chemical reactor based on an amount of solar energy available indicated by sensors for the chemical reactor.

19. A method of generating syngas products for a chemical, comprising:

supplying biomass particles into one or more tubes in the chemical reactor;

driving an endothermic gasification reaction of the particles of biomass flowing through the tubes of the chemical reactor by primarily heat radiation from the inner walls of the thermal receiver and the tube surfaces of the chemical reactor;

balancing the gasification reaction of biomass particles with the available energy and additional variable parameters of 1) a fixed range of particle size, 2) operating temperature of the chemical reactor, and 3) residence time of the particles in a reaction zone in the chemical reactor so that an overall biomass particle conversion remains above a threshold set point of substantial tar destruction resulting in less than or equal to 50 mg/Nm^3 of tar and gasification of greater than 90 percent of the carbon content of the particles into reaction products that include hydrogen and carbon monoxide gas; and

wherein a feedback component measures actual process parameters including the temperature of the chemical reactor and uses the these measurements in the balancing the gasification reaction of biomass particles.

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

conducting a chemical reaction in a solar driven chemical reactor having multiple reactor tubes using concentrated solar energy to drive the conversion of the chemical reactant, wherein an endothermic chemical reaction conducted in the reactor tubes includes one or more of the following: biomass gasification, steam methane reforming, methane cracking, steam ethane or naphtha cracking to produce ethylene and related olefins, or carbon dioxide reduction or water splitting, using solar thermal energy coming from a concentrated solar energy field; and

starting an entrained-flow of chemical reactants into the chemical reactor for the endothermic chemical reaction when 1) the solar energy concentrating field is aligned at an aperture of the solar thermal receiver containing the solar driven chemical reactor, and 2) the solar driven chemical reactor is at at least a minimum operational temperature of 800 degrees Celsius and preferably greater than 1000 degrees Celsius.

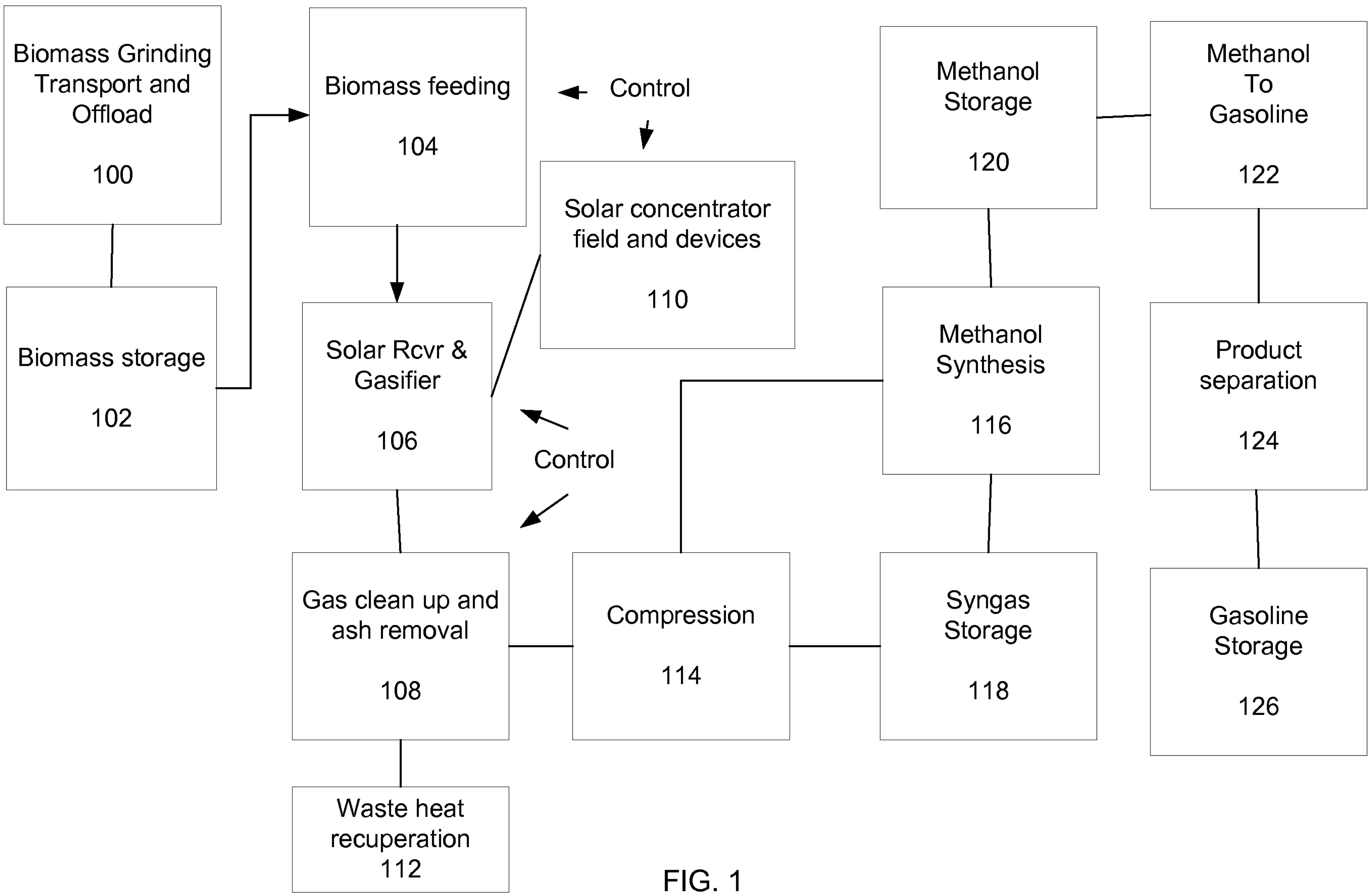
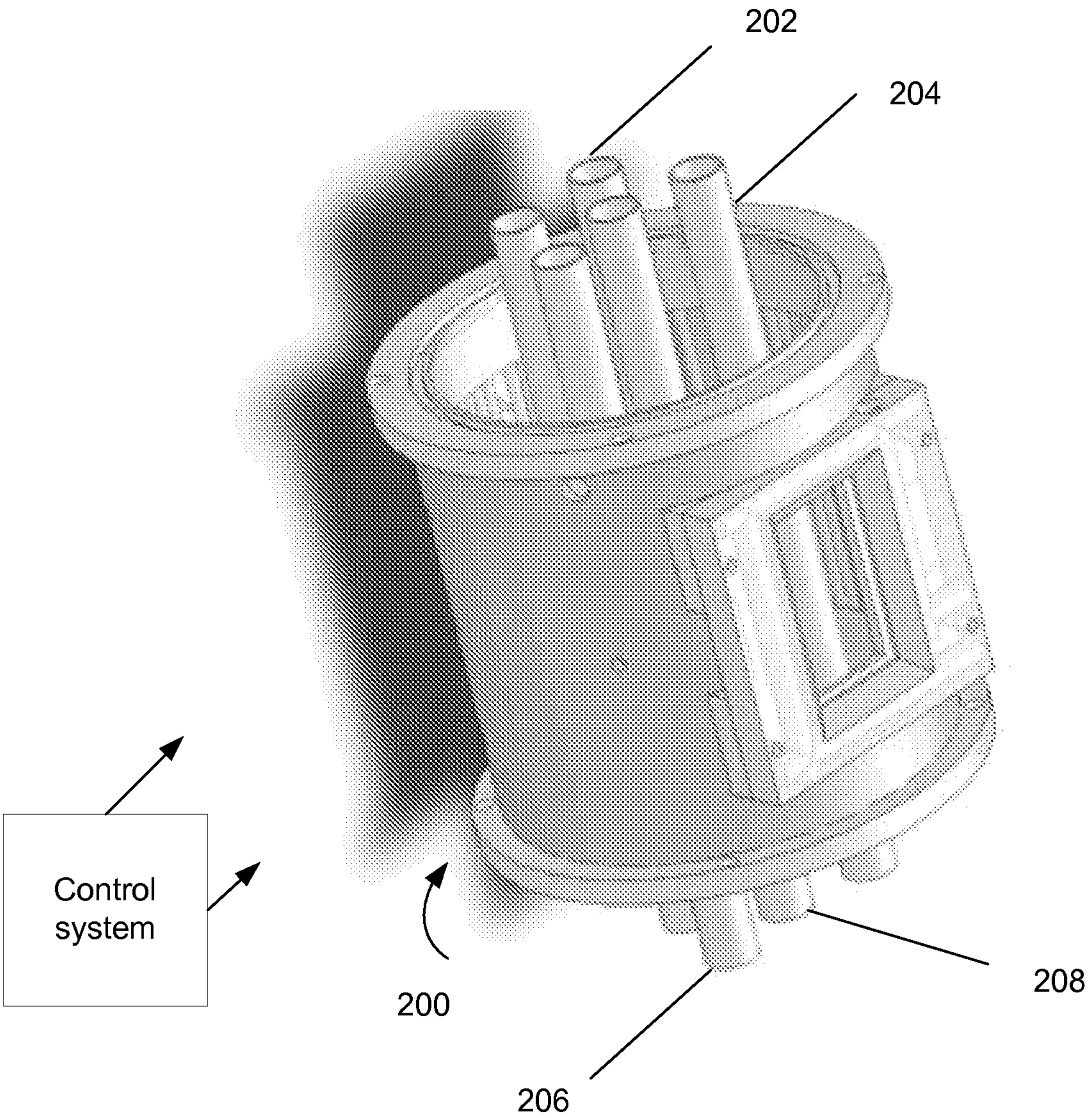

Biomass Grinding Transport and Offload
100
Biomass storage
102
Biomass feeding
104
Control
Solar concentrator field and devices
110
Solar Rcvr & Gasifier
106
Control
Gas clean up and ash removal
108
Waste heat recuperation
112
Compression
114
Methanol Storage
120
Methanol Synthesis
116
Syngas Storage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

FIG. 1



Multiple tube reactor

FIG. 2

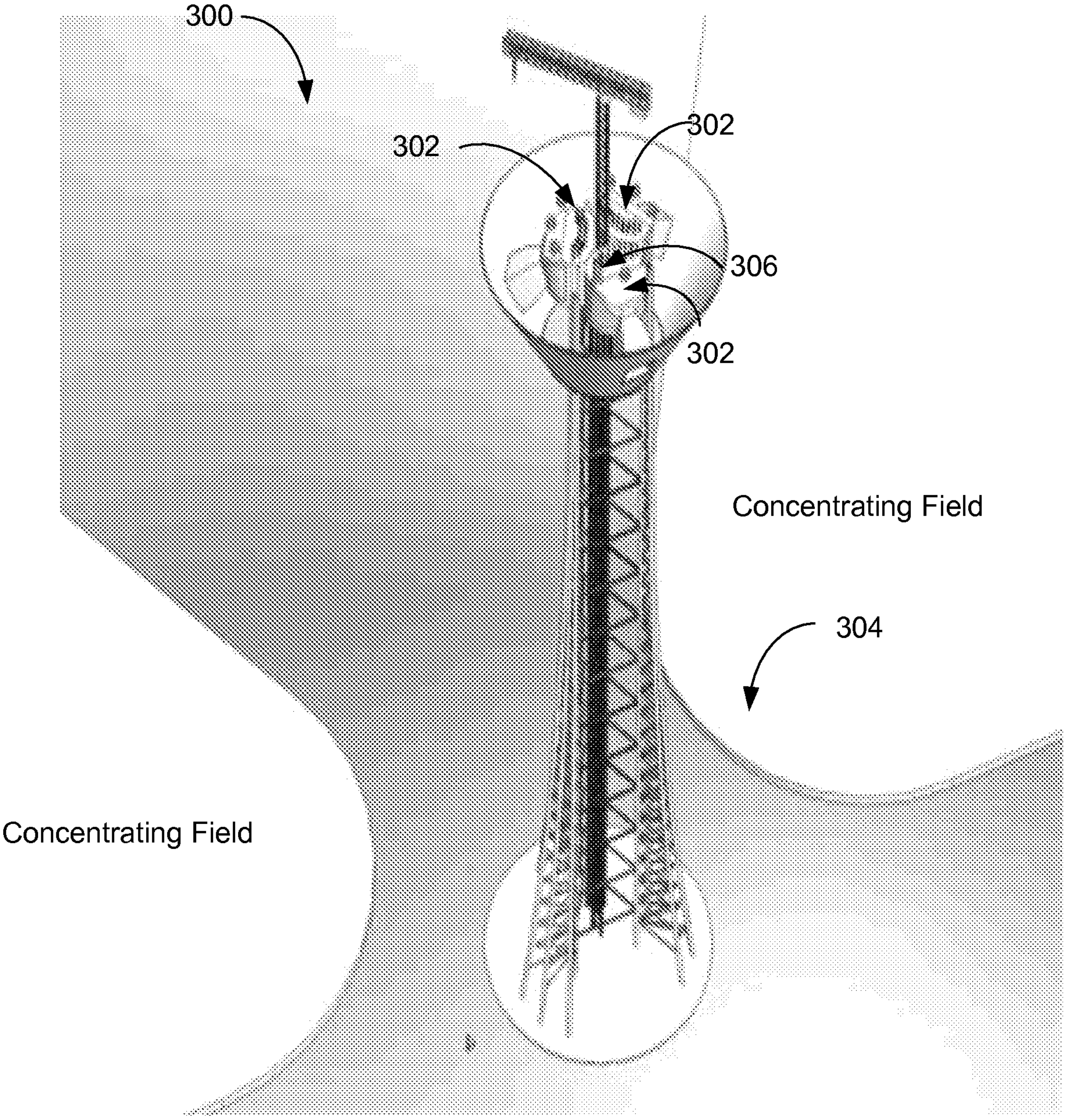

300
302
302
306
302
Concentrating Field
304
Concentrating Field

FIG. 3

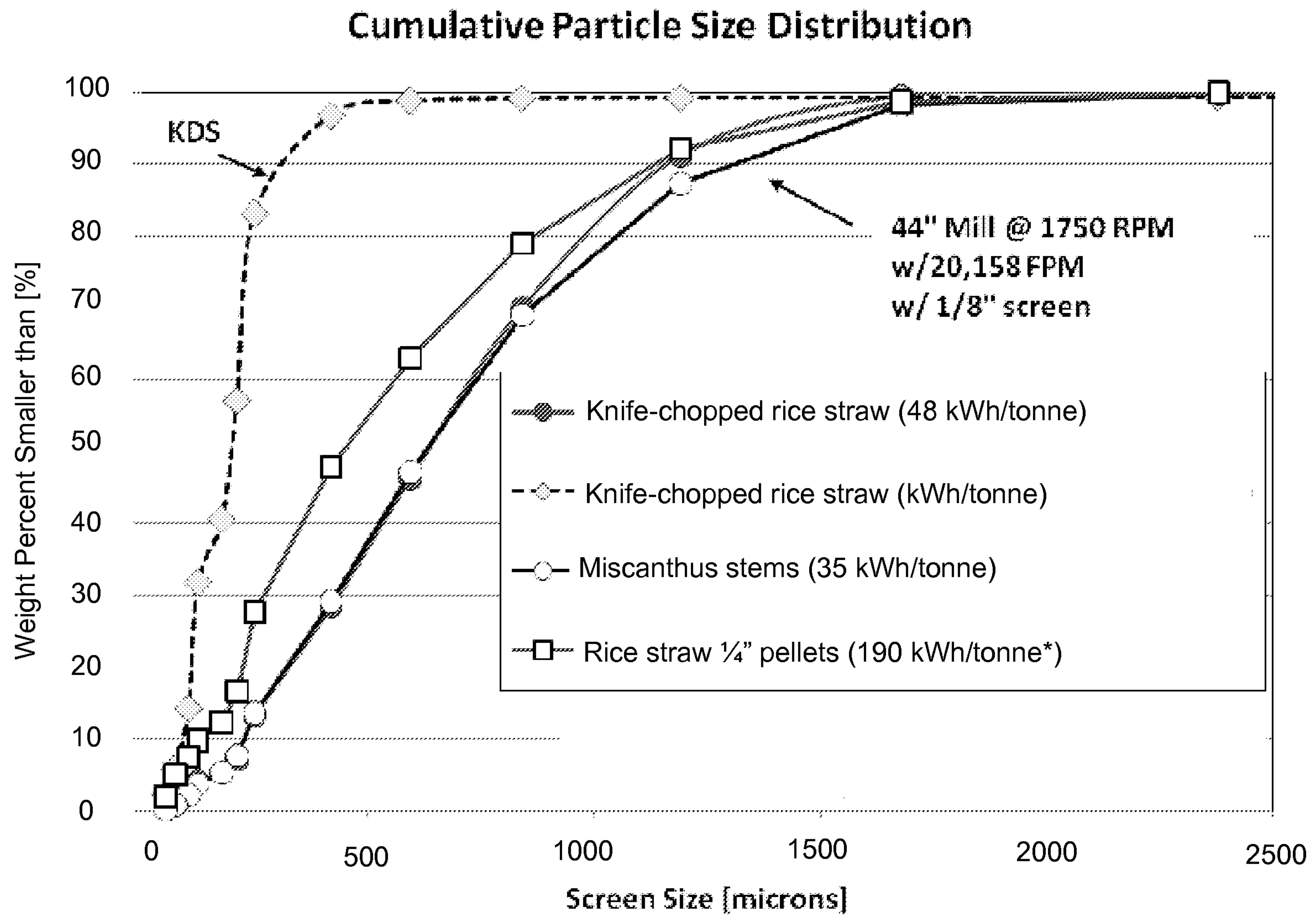

Cumulative Particle Size Distribution
Weight Percent Smaller than [%]
100
90
80
70
60
50
40
30
20
10
0
0
500
1000
1500
2000
2500
Screen Size [microns]
KDS
44" Mill @ 1750 RPM
w/20,158 FPM
w/ 1/8" screen
Knife-chopped rice straw (48 kWh/tonne)
Knife-chopped rice straw (kWh/tonne)
Miscanthus stems (35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

FIG. 4

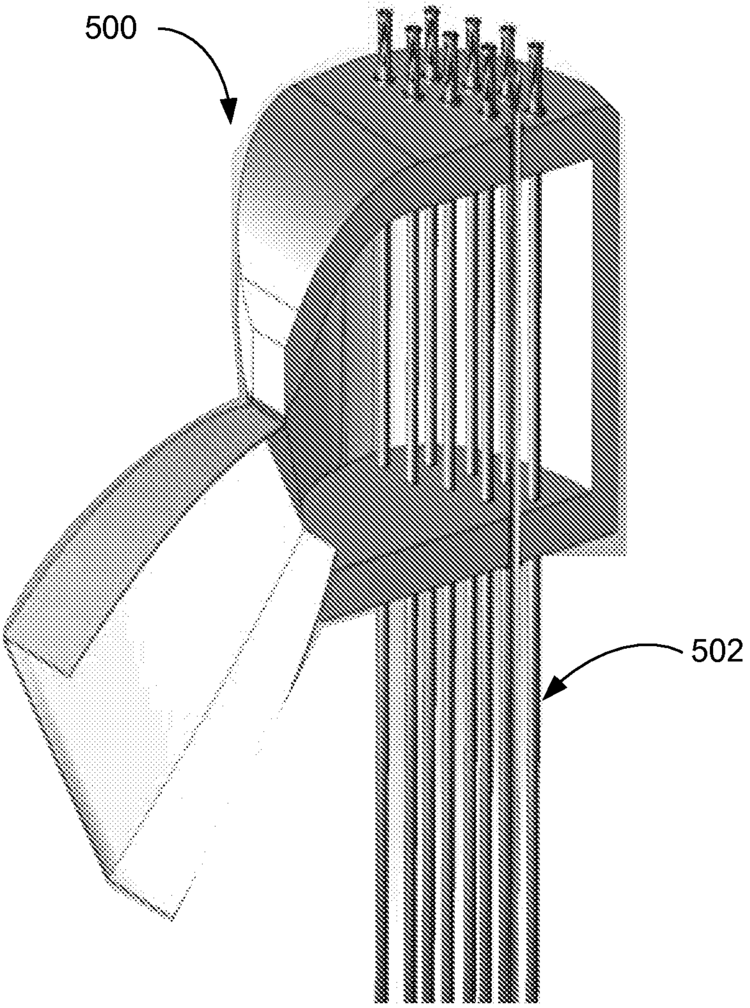


FIG. 5

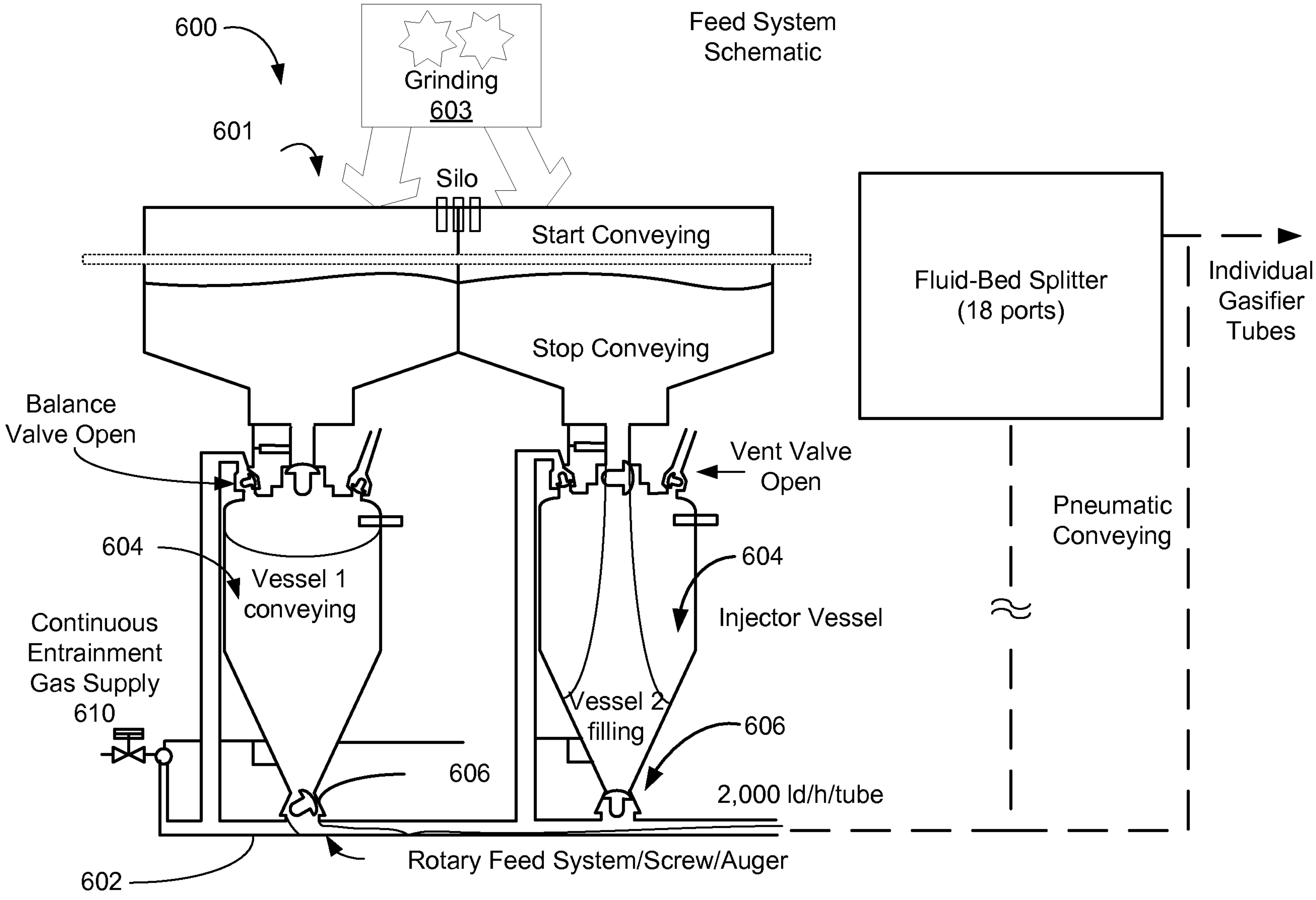

600
Grinding
603
Feed System
Schematic
601
Silo
Start Conveying
Stop Conveying
Fluid-Bed Splitter
(18 ports)
Individual
Gasifier
Tubes
Balance
Valve Open
Vent Valve
Open
Pneumatic
Conveying
604
Vessel 1
conveying
604
Injector Vessel
Continuous
Entrainment
Gas Supply
610
Vessel 2
filling
606
606
2,000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

FIG. 6a

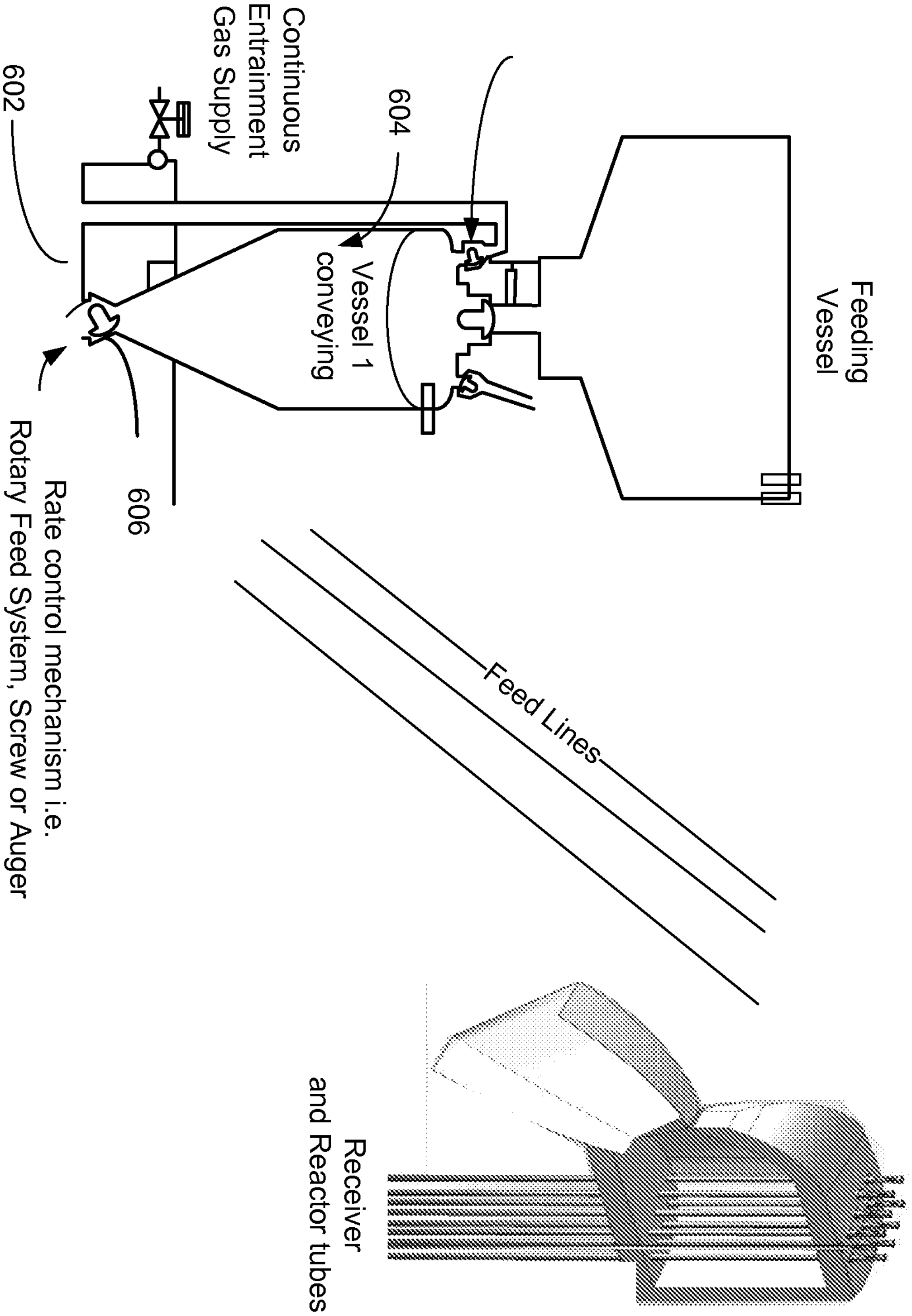

Feeding Vessel
Vessel 1 conveying
Continuous Entrainment Gas Supply
604
602
606
Rate control mechanism i.e. Rotary Feed System, Screw or Auger
Feed Lines
Receiver and Reactor tubes

Figure 6b

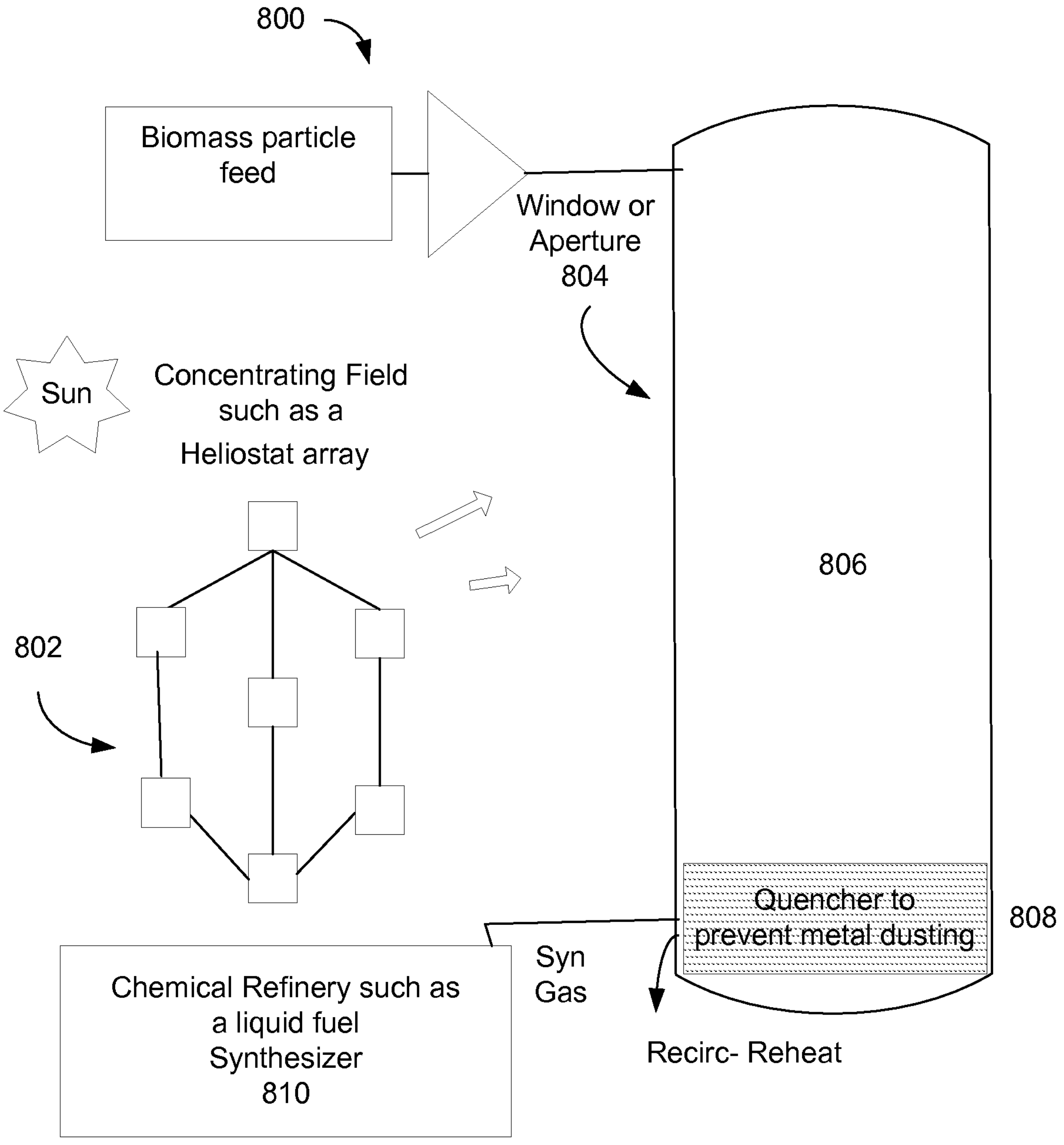

800
Biomass particle feed
Window or Aperture 804
Sun
Concentrating Field such as a Heliostat array
802
806
Quencher to prevent metal dusting
808
Syn Gas
Recirc- Reheat
Chemical Refinery such as a liquid fuel Synthesizer 810

FIG. 7

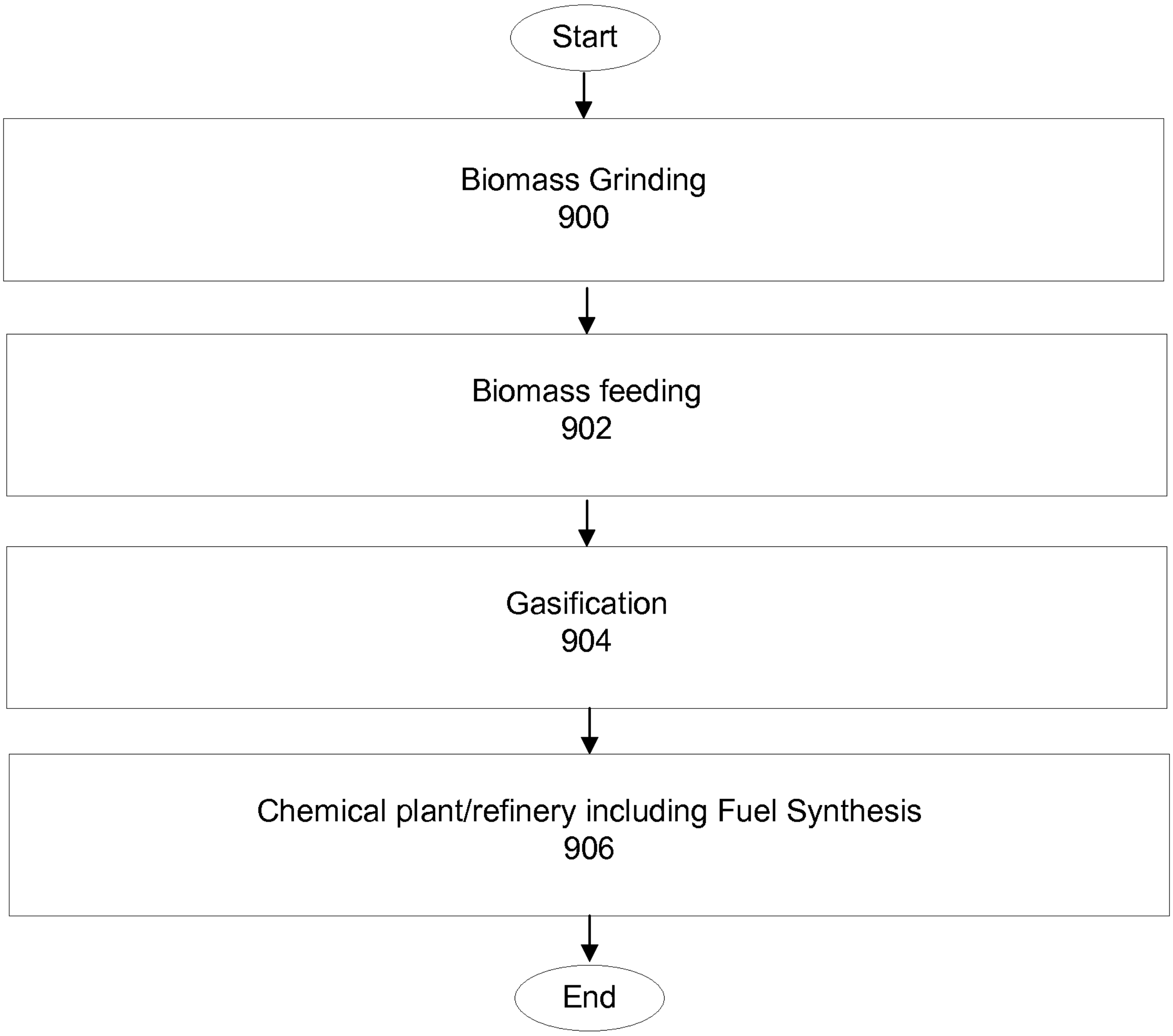

Start
Biomass Grinding
900
Biomass feeding
902
Gasification
904
Chemical plant/refinery including Fuel Synthesis
906
End

FIG. 8

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US 10/37934

A. CLASSIFICATION OF SUBJECT MATTER
IPC(8) - B01J 19/08 (2010.01)
USPC - 422/186
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- B01J 19/08 (2010.01);
USPC- 422/186

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
USPC- 422/906, 129;
Patents and NPL

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
PubWest (US Pat, PgPub, EPO, JPO: class, keyword), DialogClassic (Derwent, EPO, JPO, USPTO, WIPO: keyword), GoogleScholar; search terms: solar, photovoltaic, photochemical, plant, refinery, gasify, gasification, reactor, synthesis, mirror, array, panel, heliostat, dish, syngas, synthesis gas, weather, event, predict, lock, hopper

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	2008/0086946 A1 (WEIMER et al.) 17 April 2008 (17.04.2008), para [0009], [0010], [0016], [0027]-[0034], [0039], [0042]-[0049], [0055]-[0070], [0085]-[0090], [0095]-[0111], [0126], [0130]-[0132]	1-20
Y	JP 2002-012877A (NISHIZAKI et al.) 15 January 2002 (15.01.2002), para [0006]-[0011]	1-20
Y	US 4,455,153 A (JAKAHI) 19 June 1984 (19.06.1984), col 4, ln 61-68; col 5, ln 23-36; col 11, ln 57-66; col 14, ln 58-62;	3, 4, 11
A	US 2007/0098602 A1 (HAUETER et al.) 03 May 2007 (03.05.2007), entire document	1-20
A	US 2006/0140848 A1 (WEIMER et al.) 29 June 2006 (29.06.2006), entire document	1-20
A	US 5,647,877 A (EPSTEIN) 15 July 1997 (15.07.1997), entire document	1-20
A	ESSER, et al. "The Photochemical Synthesis of Fine Chemicals with Sunlight." Angewandte Chemie, International Edition English, 1994, Vol. 33, pp. 2009-2023.	1-20
A	SU 1763814 A1 (GOPIENKO et al.) 23 September 1992 (23.09.1992), Abstract	1-20
A	US 4,415,339 A (AIMAN et al.) 15 November 1983 (15.11.1983), entire document	1-20

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

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

Date of the actual completion of the international search
19 July 2010 (19.07.2010)

Date of mailing of the international search report
09 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