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(54) Title: SYSTEMS AND METHODS FOR AN INDIRECT RADIATION DRIVEN GASIFIER REACTOR & RECEIVER CONFIGURATION

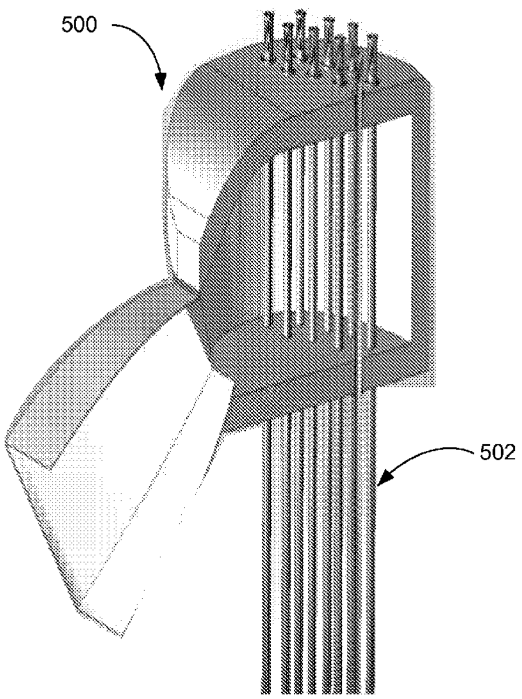

FIG. 5

(57) Abstract: A method, apparatus, and system for a solar-driven chemical plant are disclosed. Some embodiments may include a solar thermal receiver to absorb concentrated solar energy from an array of heliostats and a solar-driven chemical reactor. This chemical reactor may have multiple reactor tubes, in which particles of biomass may be gasified in the presence of a carrier gas in a gasification reaction to produce hydrogen and carbon monoxide products. High heat transfer rates of the walls and tubes may allow the particles of biomass to achieve a high enough temperature necessary for substantial tar destruction and complete gasification of greater than 90 percent of the biomass particles into reaction products including hydrogen and carbon monoxide gas in a very short residence time between a range of 0.01 and 5 seconds.

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1. An apparatus, comprising:

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

an indirect radiation driven geometry in the form of the cavity wall of the thermal receiver integrates and locates the chemical reactor inside the receiver, where the inner wall of the receiver cavity and the reactor tubes exchange energy primarily by radiation creating an oven effect, allowing for the reactor tubes to achieve a fairly uniform temperature profile; and an exit of a gasification zone in the multiple reactor tubes, wherein reaction products have a temperature from the exit of the gasification zone that equals or exceeds 900 degrees C.

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

wherein the thermal receiver is a solar thermal receiver aligned to absorb concentrated solar energy from one or more solar energy concentrating fields including 1) an array of heliostats, 2) solar concentrating dishes, and 3) any combination of the two, where the solar thermal receiver has cavity walls;

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

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

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

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

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

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

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

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

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

a material making up the reactor tubes possesses high emissivity ($\varepsilon>0.8$), high thermal conductivity (>1 W/m-K), moderate to high heat capacity (>150 J/kg-K), wherein the one or more apertures are part of an outer shell of the receiver and the material making up the reactor tubes is also resistant to the oxidizing air environment in the cavity and the reducing environment of the biomass gasification reaction.

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

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

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

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

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

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

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

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

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

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

a downdraft geometry to the multiple reactor tubes in which the biomass particles fall through the downdraft reactor design, where the downdraft permits disengagement of volatile alkali and tar components prior to cooling and remediation on the non-volatile ash, wherein the reactor tube walls are at a temperature of greater than the 900 degrees C with high heat transfer rates that allow the biomass particles to achieve the high temperatures necessary for tar destruction and complete gasification in the very short residence times of 0.01 seconds to 5 seconds.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

an on-site fuel synthesis reactor that is geographically located on the same site as the chemical reactor and integrated to receive the hydrogen and carbon monoxide products from the gasification reaction, wherein the on-site fuel synthesis reactor has an input to receive the hydrogen and carbon monoxide products in a hydrocarbon fuel synthesis process performed in the on-site fuel synthesis reactor to create liquid hydrocarbon fuels or chemicals, wherein the liquid hydrocarbon produced from the on-site fuel synthesis reactor is one or more of jet fuel, dimethyl ether (DME), gasoline, diesel, mixed alcohol, methanol, synthetic natural gas in liquid form, hydrocarbon chemicals, and heating oil, where the on-site fuel synthesis reactor being integrated with the solar driven chemical reactor allows a fraction of the concentrated solar energy from the array of heliostats to be stored as an easily transportable and stable chemical energy source in the liquid hydrocarbon fuel form.

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

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

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

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

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

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

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

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

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

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

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

18. A chemical reactor, comprising:

a thermal receiver having a cavity with an inner wall;

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

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

an exit of a gasification zone in the multiple reactor tubes, wherein reaction products have a temperature from the exit of the gasification zone that equals or exceeds 900 degrees C, and the multiple reactor tubes in this chemical reactor design increase available reactor surface area for radiative exchange to the biomass particles, as well as inter-tube radiation exchange.

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

wherein the thermal receiver is a solar thermal receiver aligned to absorb concentrated solar energy from one or more solar energy concentrating fields including 1) an array of heliostats, 2) solar concentrating dishes, and 3) any combination of the two, where the solar thermal receiver has cavity walls;

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

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

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

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

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

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

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